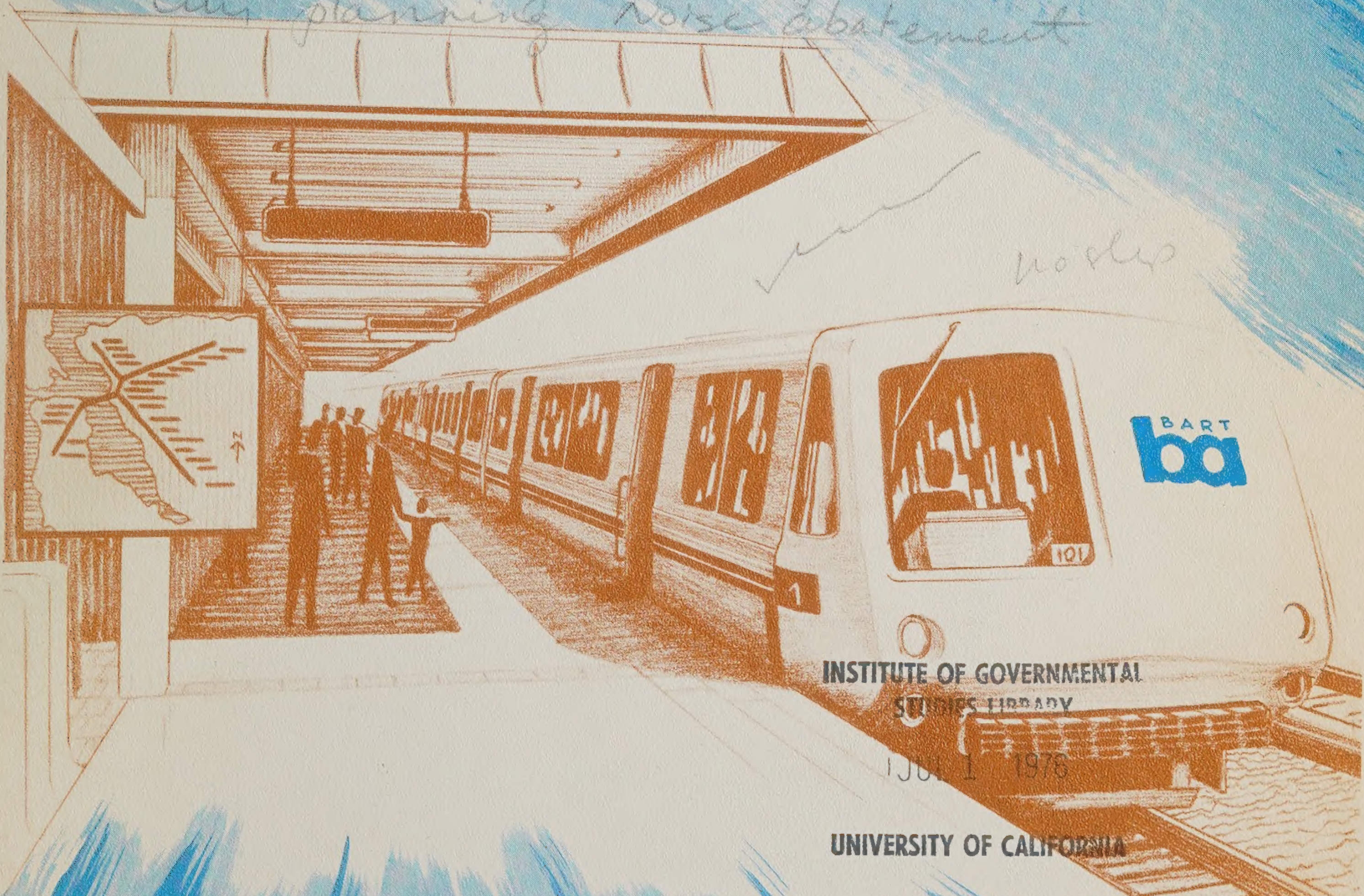
bart
impact
program

ACOUSTIC IMPACTS OF BART: INTERIM SERVICE FINDINGS

Street railways S.F. bay area
City planning noise abatement



The BART Impact Program is a comprehensive, policy-oriented study and evaluation of the impacts of the San Francisco Bay Area's new rapid transit system (BART).

The program is being conducted by the Metropolitan Transportation Commission, a nine-county regional agency established by state law in 1970.

The program is financed by the U.S. Department of Transportation, the U.S. Department of Housing and Urban Development, and the California Department of Transportation. Management of the Federally-funded portion of the program is vested in the U.S. Department of Transportation.

The BART Impact Program covers the entire range of potential rapid transit impacts, including impacts on traffic flow, travel behavior, land use and urban development, the environment, the regional economy, social institutions and life styles, and public policy. The incidence of these impacts on population groups, local areas, and economic sectors will be measured and analyzed. The benefits of BART, and their distribution, will be weighed against the negative impacts and costs of the system in an objective evaluation of the contribution that the rapid transit investment makes toward meeting the needs and objectives of this metropolitan area and all of its people.

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BART IMPACT PROGRAM

ACOUSTIC IMPACTS OF BART INTERIM SERVICE FINDINGS

MARCH 1976

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PREPARED FOR

U. S. DEPARTMENT OF TRANSPORTATION

AND

U. S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

NOTICE

PREPARED BY

BOLT BERANEK & NEWMAN, INC.

SUBCONTRACTOR TO

GRUEN ASSOCIATES, INC.

AND

DE LEUW, CATHER & COMPANY

UNDER CONTRACT WITH THE

METROPOLITAN TRANSPORTATION COMMISSION

FOR THE

U. S. DEPARTMENT OF TRANSPORTATION

AND THE

U. S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

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16. Abstracts

This report documents the findings and methodologies developed during a study of BART sound and vibration levels. The findings focus on: delineation of impacted regions, major factors affecting BART-generated sound, prototype vs. operational sound levels, BART vs. other transportation sound sources and BART-generated vibration levels. BART-generated sound levels were derived from direct wayside measurements and indirectly from on-board recording of sound levels throughout the BART system. Ambient community sound levels were based on predictive techniques verified by field measurements.

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PREFACE

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The Environment Project focuses on the effects of BART's physical presence on its surroundings. Environment is defined broadly to include five components: acoustic, atmospheric, natural, social and visual. Within each of these components the Environment Project will address two related phenomena:

- Direct and indirect physical effects upon the environment brought about by the BART system

- Social and psychological consequences of these physical changes to the environment

This report - Acoustic Impacts of BART, includes an assessment of both sound and vibration. It is a technical report containing a detailed presentation of acoustic findings and the study methodology employed. This report is an interim document as study of BART's acoustic impacts is continuing. Phase I, covered in this report, concentrated on BART's acoustic effects on the physical dimensions of the Bay Area. However, measurements and assessment were made under interim BART operations. In Phase II additional assessment will be made as operational conditions change. Also in Phase II, people who live and work next to the BART system will be studied as to how they perceive and respond to impacts. And finally, in Phase II a comparison of BART's impacts with those of other means of providing a similar level of public transportation service will be made. The findings as derived here formed part of the basis for the development of Phase I conclusions regarding BART's overall environmental impacts. These interpretations are reported in the Phase I report - Environmental Impacts of BART.

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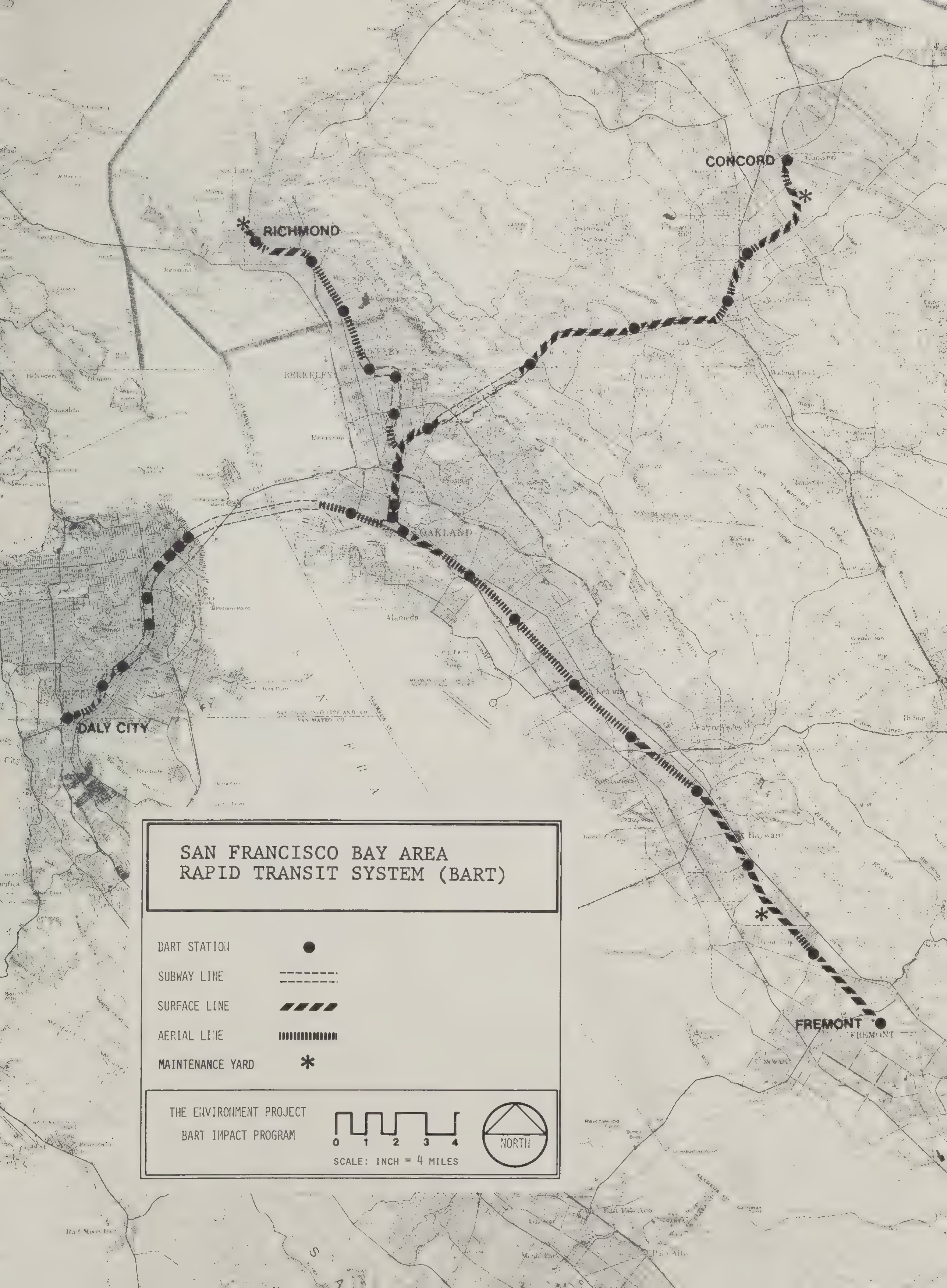
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BART STATION
SUBWAY LINE
SURFACE LINE
AERIAL LINE
MAINTENANCE YARD
THE ENVIRONMENT PROJECT
BART IMPACT PROGRAM
0 1 2 3 4
SCALE: INCH = 4 MILES
NORTH

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SUMMARY

INTRODUCTION

The acoustic environment is defined to include both sound and vibration. BART is a dynamic mechanical system, generating both sound and vibration; as such it can add to the level and variety of the acoustic environment.

The Phase I acoustic study concentrated on the sound impacts of BART trains, and involved extensive instrument measurements and statistical analyses. Lesser emphasis was placed on vibration caused by the trains and sound and vibration caused by feeder buses and autos. The preliminary studies of these secondary topics will be expanded as required during Phase II.

SOUND

BART's impacts on community sound levels focused on several key topics:

- Prior community sound levels along BART lines.
- Location and intensity of present impacts.
- Nature and location of likely future changes.
- Major and other contributory causes of impacts.
- Comparison of BART's actual impacts with original predictions and other travel modes.

Methodology

In order to provide a systemwide sound impact assessment within available resources, an innovative approach was developed and applied. Its key features were as follows:

- Definition of sonic impact.
- Selection of impact measures.
- Estimation of background community sound levels.
- Measurement of BART sound levels.

It is a characteristic of sound that when one sound is joined by another of equal intensity, the resultant increase in intensity is barely perceptible. This effect applies to a steady sound. By extension, it is taken to apply also to two independently varying sound sources whose averages over time are equal. In order for the second sound to have a significant impact, it must be substantially more intense than the original or "background" sound. Thus, sonic impact, as defined in this study, occurs when the sound generated by BART exceeds the existing level in the community.

There is continuing controversy over the selection of measures appropriate for assessment of transit's sonic impacts. Instantaneous or maximum sound level--the loudest sound reached by a passing train--could be used. However, this would not consider how often the trains pass, or how sound might vary from one train to another. In addition, background community sound intensity also varies, for example, through noise of construction, motorcycles, trucks and sirens; thus, sound measures should be consistent between BART and community sound if the results are to be meaningful. For example, it would be misleading to rely on comparison of BART's maximum sound with an average community sound. On the other hand, use of averages for both BART and community sound levels tends to mask the actual momentary effect of the passage of a BART train.

Obviously there is no easy "best" approach. For this study's purposes a standard measure, the hourly "equivalent sound level" (L_{eq}), was selected for BART sound based on its prior use in railway freight and aircraft take-off noise assessment (pp. 63-64). This measure yields an average hourly sound intensity due to BART train pass-bys only.

As a basis for comparison, corresponding community sound levels were measured with the "daytime equivalent sound level" (L_d). This is a logarithmic average[1] of the hourly L_{eq} values due to factors other than BART; it serves to remove the effect of hour-to-hour variations in community sound during BART's current (daytime) hours of operation.[2]

Community sound levels systemwide were estimated first using recently-identified relationships between population density, traffic levels, and resulting sound levels. These were verified by 24-hour sound measurements at 12 points throughout the system (pp. 8-20).

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[1] Logarithmic average is defined on p. 64.

[2] At the time this portion of the study was conducted, BART's operations were only during daytime hours. In November 1975, BART began nighttime operations.

BART sound levels were established in a similar two-part measurement program. First, train sound level variations were recorded on board trains running throughout the BART system. This "sound profile" by location was then adjusted to actual wayside dB(A)[1] values through a program of wayside measurements of BART train pass-bys at some 15 points throughout the system (pp. 51-59).

Issues and Findings

What are the community sound levels along the system when BART is not operating?

The wayside communities along BART range from densely-populated residential and commercial/residential areas such as Daly City and Albany-El Cerrito to relatively sparsely-populated suburban residential communities such as found in Pleasant Hill, Walnut Creek and Fremont. However, adjacent to virtually all of the BART system are other major transportation arteries such as freeways, major arterial streets, and railroad lines. With the exception of the portion of the system near Fremont and Union City, where BART is above ground and runs near low-density residential areas, at least one other major transportation artery parallels the BART tracks. This indicates that, for the most part, BART does not run in areas otherwise classifiable as "very quiet." This was supported by available statistical relationships and field measurements which yielded a range of L_d values of 55 to 70 dB(A) in communities alongside the system (pp. 4-20).

What is BART's present impact on community sound levels?

At a distance of 50 feet from the track centerline, the equivalent sound level (L_{eq}) generated by BART was found, depending upon the location, to range from below the community L_d to a maximum of 12 dB above it. At a distance of 250 feet from the tracks, the BART-generated sound level did not exceed the community level by more than 4 dB in any location.

Houses further removed from the BART system are generally shielded from BART-generated sounds by the first row of houses or other buildings adjacent to the BART line. Because of this factor, the acoustic impact of BART is generally confined to an area that extends substantially less than 250 feet away from the BART system. In fact, in most situations, the impact is most likely limited to only the first row of houses or other structures along the system.

[1] Definition of dB(A) is found on p. 62.

The relationship between the L_{eq} (generated by BART) and the range of L_d in the community is illustrated on Figure A. Shown are the L_{eq} values that currently exist at a distance of 50 feet from the centerline of the track along the BART system. Additionally, the range of the mean L_d levels in the communities adjacent to the BART system is indicated by the shaded band. The protrusion of the line indicating BART sound above the community band indicates that a perceptible impact may be occurring. The higher the BART levels protrude above the community levels, the greater the likelihood of impact.

Possible acoustic impact (defined as BART L_{eq} exceeding community L_d by not more than 5 dB) is expected along approximately 30% of the total BART system; along 10% of the system acoustic impact is considered probable (defined as BART L_{eq} exceeding the community L_d by more than 5 dB). Population figures from the 1970 census data indicate that approximately 15,000 people live within these affected regions (p. 40).

How is this impact likely to change with BART's planned future addition of evening service and more frequent daytime trains?

The impact just described was based on daytime operations and headways of 6 or 12 minutes. Future plans for BART indicate that both train headway and hours of operation may be expected to change. The reduction of headways from 6 minutes to 2 minutes would result in an increase in L_{eq} of approximately 5 dB (p. 40). This would mean that rather than at a few locations, the BART-generated L_{eq} may be expected to exceed the community L_d by 10 dB along much of the system located in residential areas.

Late night and early morning sound levels in the community tend to be on the order of 8 to 10 dB below the daytime levels (p. 41). Thus, nighttime BART operations will be much more evident in the community. Even with 20-minute headways, as have been projected for some of the late night operations, wayside BART L_{eq}s of 62 dB(A) at a distance of 50 feet from the centerline of the track are expected. Assuming that the community sound levels will drop by 10 dB during the late night hours, the L_{eq} of nighttime BART operations could well be on the order of 15 dB or more above the community nighttime equivalent sound level (L_n).

What aspects of BART's operation are the main causes of these sound impacts?

Many individual factors contribute to the sound levels generated by the BART system. A significant portion of this study was devoted to identifying the more important of these factors. Three primary factors affecting wayside sound levels were identified: train speed, track configuration and switches (pp. 20-29). Of these, train speed was found to have the greatest range of effect. The maximum A-weighted sound level (L_{max}) at the wayside of the BART system was shown to be proportional to 28 $\log_{10}$ of the

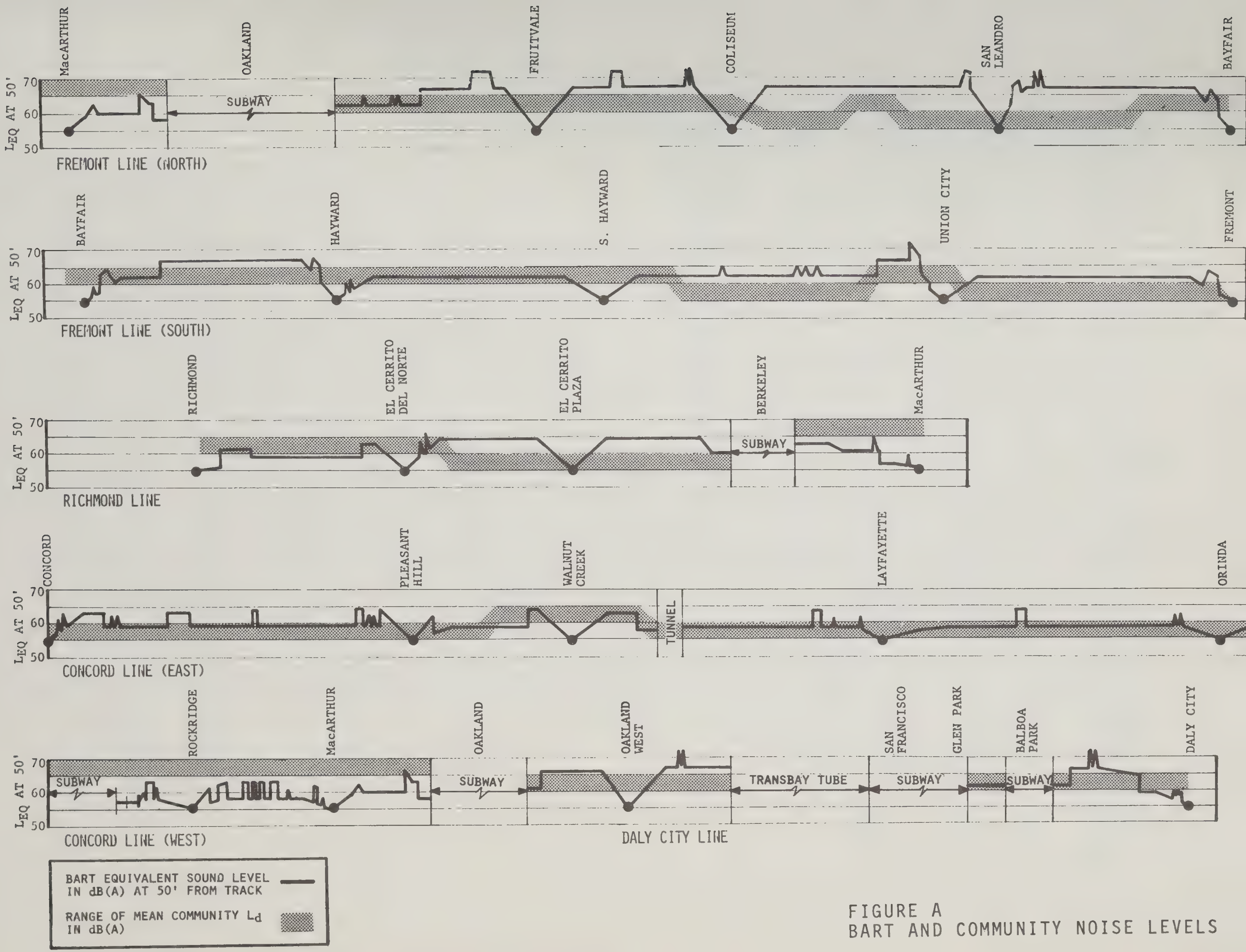


FIGURE A
BART AND COMMUNITY NOISE LEVELS

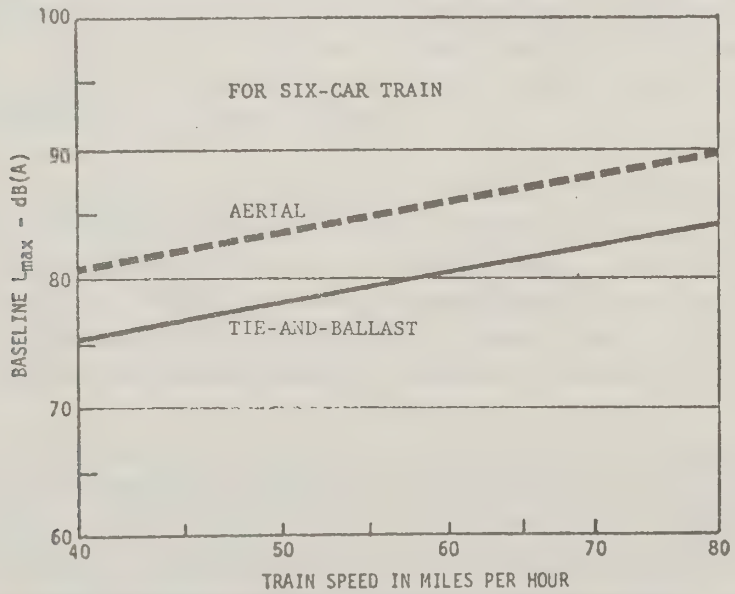
train speed. This dependence on speed indicates that the wayside L_{max} will vary approximately 8 dB from the locations having the lowest average operational speed on the system (36 mph) to those with the highest average operational speed (70 mph).

The track configuration--concrete aerial structure versus at-grade (tie and ballast)--was also found to have a significant effect on sound generation. For trains traveling at equal speeds, the L_{max} adjacent (50 feet) to tie-and-ballast track is approximately 5 dB lower than the L_{max} adjacent to track on aerial structures.

The relationship between train speed, track configuration and wayside sound level is indicated for a six-car train by Figure B. The figure shows that for a train traveling 65 mph on tie-and-ballast track, the projected L_{max} would be 82 dB(A). For a train operating at the same speed on aerial structure, the L_{max} would be 87 dB(A).

FIGURE B

BART MAXIMUM SOUND LEVEL (L_{max})
AS A FUNCTION OF TRAIN SPEED
AND TRACK CONFIGURATION



On either type of track the presence of a switch (turnout or crossover) results in an additional 5 dB increase in the wayside L_{max} in the immediate area.

What other factors also affect the wayside sound levels of BART trains?

The wayside sound levels along the BART system exhibit variations which cannot be attributed to train speed, track type or switches. Some of these

variations are due to the differences in sound levels produced by individual trains (p. 22). The standard deviation of the L_{max} of individual trains about the mean L_{max} for all trains is approximately 1.5 dB. This increase indicates that some 90 percent of the vehicles of the BART system will produce wayside L_{max} values within ± 3 dB of the mean. (Further analysis will be done in Phase II to provide information on the effects of aging and maintenance.)

The first row of houses or other buildings adjacent to the BART line tend to shield those residences further removed from the system from BART-generated sounds. The shielding offered by the first row of structures is on the order of 5 to 10 dB (p. 23). Where the houses are fairly close together (as is typical in the Bay Area), the degree of shielding would tend to be nearer the 10 dB value than the 5 dB value.

The median L_{max} observed adjacent to curves with a radius of less than 4,500 feet tended to be approximately 5 dB higher than was observed adjacent to straight track. Since this tendency was noted only for approximately half of the vehicles observed (no correlation was found between vehicle speed and the vehicles exhibiting higher sound levels), these findings must be considered at best tentative. Furthermore, an increase in the L_{max} was observed adjacent to several portions of curved track where the radius was considerably in excess of 4,500 feet. Subjective observation of these increased levels indicates that a factor accounting for the acceleration or deceleration of the train through the curve may also affect wayside L_{max} (pp. 29-30).

No significant increase in the L_{max} created by BART pass-bys was observed in the vicinity of tunnels. The reverberation of sound within the tunnel and subsequent release of this sound energy to the atmosphere at the tunnel entrance, however, did increase the amount of time which the sound level remained within 10 dB of its maximum. Thus, due to the longer duration of the sound, the L_{eq} was increased (p. 30).

In general, it was found that the sound generated by automobile traffic into and out of the stations was virtually lost in the background of other vehicular operations in the community. A similar finding was reached for BART feeder bus traffic. That is, the sound levels generated by buses at the BART stations were less than or equal to sound levels already present on the arterials near BART stations due to other transportation sources (pp. 30-31).

Figure C is used in a manner similar to Figure B, but shows equivalent sound level (L_{eq}) rather than maximum sound level (L_{max}). For similar operating conditions, such as a six-car train traveling 65 mph on tie-and-ballast at six-minute headways, the L_{max} would be 82 dB(A), whereas the L_{eq} would be 62 dB(A). The data on Figure C indicates how the L_{eq} values vary as a function of different train speeds and headways.

FIGURE C
BART EQUIVALENT SOUND LEVEL (L_{eq})
AS A FUNCTION OF TRAIN SPEED AND HEADWAYS

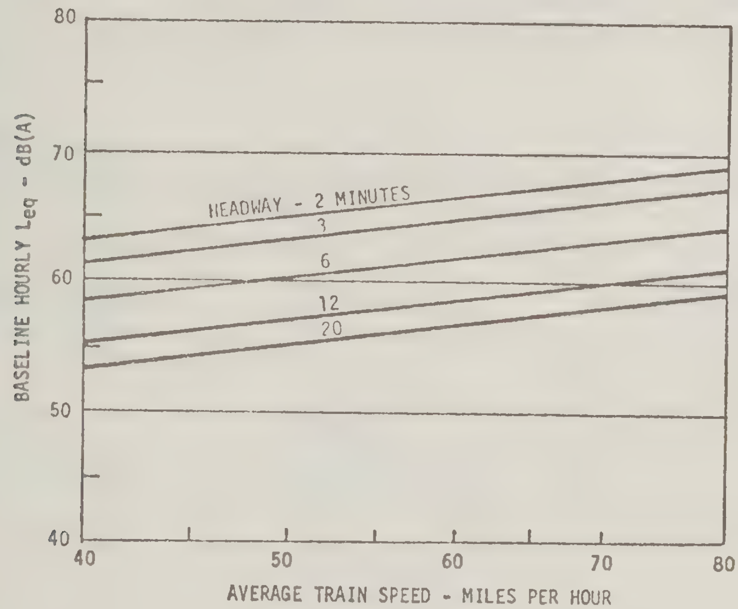


Table A lists corrections that can be applied to Figure C to account for differences in configuration and train length. For example, the L_{eq} for eight-car trains operating at 65 mph, at six-minute headways, over a switch on an aerial section would be 62 + 1 + 5 + 5 = 73 dB(A).

TABLE A
CHANGES IN EQUIVALENT SOUND LEVEL (L_{eq})
BASED ON VARIATIONS IN OPERATING CONDITIONS

CONDITION	dB(A)
Tie & Ballast (Berm or Grade)	+0
Aerial Structure	+5
Switch on Berm or Grade	+3
Switch on Aerial	+5
Curve (Radius < 4500')	+5
2 Car Train	-3
4 Car Train	-1
6 Car Train	+0
8 Car Train	+1
10 Car Train	+2

How do BART's sonic impacts compare with those of buses and autos?

Using the data on BART and a highway traffic model developed for the Highway Research Board, the following table was developed to illustrate the sound levels for three different transportation modes conveying 7,000 passengers per hour (BART's nominal capacity) past a given point.

TABLE B
COMPARISON OF BART AND OTHER TRANSPORTATION MODES

Transportation Mode	Conditions	Sound Level (L_{eq}) @ 50' from Noise Source
BART	Ten trains (10 cars each, 6 minute headways), 70 mph	70 dB (A) - Aerial 65 dB (A) - Tie-and-Ballast
Passenger Cars	4,600 vehicles (1.5 Passengers/ Vehicle), 45 mph	73 dB (A)
Commute Buses	150 buses (45 Passengers/ Vehicle), 45 mph	71 dB (A)

The difference in sound between BART in an aerial configuration and the other two modes is not appreciable. However, BART trains operating on tie-and-ballast (at-grade or embanked) track are found to be significantly quieter than autos or buses carrying the same volume of passengers per hour.

How does actual BART-generated sound compare with earlier expectations based on measures of prototype cars?

Significant differences between prototype and operational systems are often encountered. The close control exercised over prototypes during the initial testing stages is often impractical for full-scale operational systems. Therefore, the degree to which the operational BART system performs as was projected from prototype measurements is of importance in the establishment of confidence limits on projections for future transit systems.

In a report prepared for BART, projections were made concerning the wayside sound levels that might be expected due to BART operations. These projections were made on the basis of a series of measurements of prototype BART vehicles operating on the initial aerial test track. This report indicated that at a distance of 50 feet from a train on an aerial structure at 70 mph, a wayside L_{max} of 87 dB(A) might be expected. This projected level is indeed the same as has been found for the mean L_{max} due to the

operation of six-car trains on aerial structures. The 1969 report, however, indicated that the expected wayside L_{max} adjacent to tie-and-ballast track would be only 2-3 dB quieter than the L_{max} of aerial track. However, this study indicated a 5 dB difference exists between aerial and tie-and-ballast track.

VIBRATION

The primary goals of the vibration-related portion of the study were to examine the likelihood of community impact due to BART train-generated vibrations and to gather baseline data for later (Phase II) assessment of BART train aging and maintenance effectiveness.

Methodology

No significant vibration impacts were expected to be found, in view of BART's observably smooth riding characteristics and the general lack of available evidence of community concern on this topic. Consequently, the Phase I study was simple in design in comparison with that of the sound impact study: ground-borne vibrations were monitored by instrument at two sites, one with BART in a typical aerial format and the other a subway. Monitoring periods of several hours and approximately 35 train pass-bys were used, in order to assure data representative of a variety of BART vehicles (pp. 41-43, 58-60).

Issues and Findings

What wayside vibration effects are caused by BART trains operating in subway and aerial configurations?

Vibration measurements on a structure above the BART subway line (Mission Street in San Francisco) indicated that the more prominent of the BART pass-bys could be identified and separated from other vibrations caused by vehicular traffic. The overall vibration velocity level in the 5-50 Hertz (Hz)-region was not noticeably greater for BART pass-bys than for vehicular traffic on the street above. The vibration velocity levels seldom, if ever, exceeded what is commonly considered the threshold of sensory reactions to vibrations.

Vibration levels measured near the base of an aerial structure in a residential area showed a marked increase during the pass-by of each BART vehicle. The overall vibration velocity level tended to rise on the order of 15-20 dB above the ambient as BART vehicles passed by. These BART pass-by levels measured were of the same order of magnitude as those caused by delivery trucks operating in the neighborhood on an adjacent street.

The overall vibration velocity levels measured at both locations were dominated by components in the 16-20 Hz and 25 to 35 Hz ranges. The components in the lower range correspond to wheel rotational frequencies of the train wheels. "Flat spots" on wheels may account for this. The source of the higher frequency component is less certain and will require further study.

The magnitudes of the BART-induced vibration levels at both measurement locations were nearly the same as peak levels due to vehicular traffic on the adjacent streets. The magnitudes of the vibration input of street vehicles at both locations are very nearly the same. This indicates, at least qualitatively, that the level of BART-induced vibration is of the same order of magnitude at both locations.

Vibration effects of rapid transit systems are most often considered as being a problem near subway portions of such systems. Ground-borne vibrations in the community near aerial structures have commonly been considered to be of less significance. Despite the limited measurement program undertaken here, this study's initial findings appear to contradict this presumption. To verify these findings the vibration study will be extended through further measurements and analysis in Phase II.

I. DEFINITION AND SCOPE

Transportation systems as a whole are the most pervasive noise sources in our urban environment. In the more densely populated metropolitan regions, such as the San Francisco Bay Area, the automobile has been identified as the major overall contributor to environmental noise. Public rapid transit systems, such as the Bay Area Rapid Transit system (BART), have been proposed as alternative modes of transportation for the urban environment. Since systems such as BART are proposed as substitutes for the automobile, it follows that the impact of systems such as BART on the acoustic environment of the surrounding community should be assessed.

The development of an accurate assessment of the acoustic impact of the BART system on the community requires knowledge of both the community acoustic environment independent of BART and knowledge of the sound levels produced by BART itself. Examination of the absolute levels generated by BART and of the degree to which BART-generated sound levels affect the surrounding community sound levels will allow at least a preliminary estimate of the acoustic impact of the BART system.

Quoting a recent HUD publication (Schultz, 1974), "Noise is a sound that somebody doesn't want: what is music to me may be noise to you." This statement illustrates that there is a most basic difference between sound and noise. Sound is an objective quantity that may be measured with the appropriate physical instrument, such as a sound level meter. Noise, on the other hand, is a subjective quantity and as such depends on many factors other than simply the physical magnitude of the sound. Because the social survey program to assess people's attitudes about BART in general and BART-generated sounds in particular has not been completed, the acoustic impact assessment presented in this report should be considered only tentative.

This report documents the findings, conclusions and implications developed during a study of BART sound and vibration levels. The major emphasis of this study was on BART sounds, while vibrations were examined in a rather cursory manner. A significant result of the study was that definite need for a much more comprehensive study of BART vibrations was identified. Additional aspects of BART-generated sounds have also been identified as requiring further study.

The research questions and strategy used for this study will be outlined in the following section. Next, the actual physical measures or findings obtained will be discussed. The conclusions will then be discussed and, in the next section, implications for future transit systems that may be derived from the findings and conclusions will be presented. Two final sections present a description of the methodologies used during the study and an Appendix containing background material on acoustic terminology.

II. RESEARCH QUESTIONS AND STRATEGY

The overall goal of the Phase I acoustic impact study was to define as completely as possible the location and probable severity of impacts due to BART-generated sound. An additional goal of the acoustic study was to identify the major contributing factors to BART-related sound and examine these factors relative to the formulation of guidelines for future rapid transit systems.

The primary goals of the vibration related portion of the study were to examine the likelihood of community impact due to BART-generated vibrations and to gather baseline data for possible assessment of BART train aging and maintenance effectiveness.

The assessment of the acoustic impact of the BART system on the surrounding community involves a comparison of the sound and vibration levels generated by BART with those levels that are present in the community independently of BART. Since quantitative data must be obtained, the development of an adequate field measurement program to provide meaningful information within the prescribed economic constraints was required.

The measurement program developed for this study was basically a survey program to identify the major impacts and principal influencing factors. The use of the survey method led to the development of the same quality of information that could have been obtained with an exhaustive point-by-point study of the entire system. Additionally, it was possible to place more emphasis on data analysis and interpretation. The survey strategy required that the relevance of the information being gathered with respect to the goals of the overall study be assessed. Several questions derived from the goals and objectives have served as guidelines for this purpose.

What is the contribution of BART station and train operations to the overall sound and vibration environment in its vicinity? What is the contribution of BART's feeder traffic to the overall sound environment of the affected areas? How much variation occurs in BART's sound impacts, by time of day, by location? What are the determinants governing this variation? How much variation in sound intensity and frequency significance exists between individual trains? These are all questions that were developed as initial guidelines to insure that the major impacts and factors would be identified. As the program progressed, other derivative questions were developed as the relative importance of various aspects of the system to the overall acoustic impact were determined.

III. FINDINGS

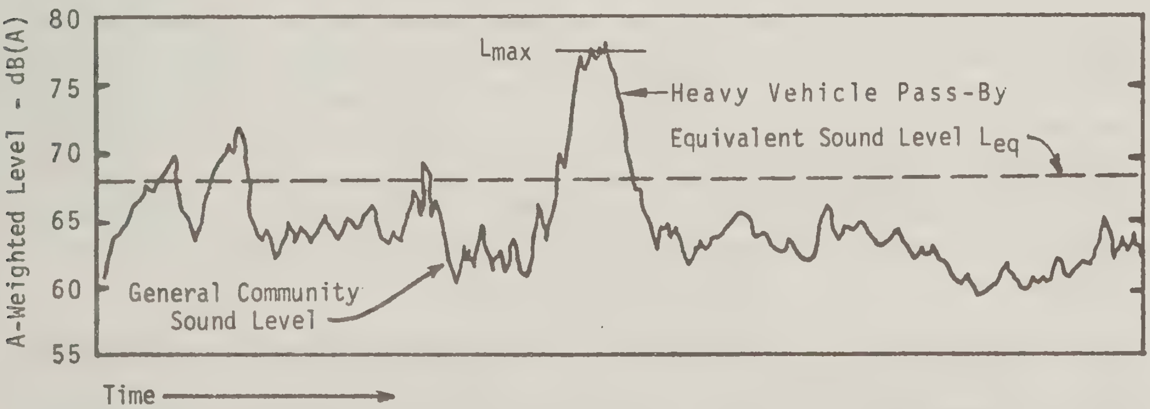
This section discusses the findings derived from the study of BART's impact on its acoustic environment. The findings relative to the community and BART sound levels individually are presented and the juxtaposition of the two is examined. Finally, findings relating to BART-generated vibrations are discussed.

DESCRIPTION OF TERMINOLOGY

A-weighted sound levels are used in this report to describe the sounds in the community with and without BART. The fact that community sounds tend to vary with time is accounted for by the use of the A-weighted equivalent sound level (L_{eq}) and the daytime equivalent sound level (L_d). "A-weighted" means, in essence, that very high and very low frequency sounds are discriminated against in the measurement procedure.[1]

The graphic recording of community sounds shown below illustrates the way L_{eq} relates to the ever-changing level of environmental sounds.

FIGURE 1
EQUIVALENT SOUND LEVEL (L_{eq}) IN RELATIONSHIP TO ENVIRONMENTAL SOUNDS



Here it may be seen that the equivalent sound level (the dotted line) lies somewhat above the level that might be judged by eye as being the average. The difference comes about because L_{eq} accounts for both the general

[1] See Appendix A for a more complete description of terms.

background level as well as intrusions above this level. The characteristics of L_{eq} are such that an area with a low background level and a few very loud intrusive sounds, such as a quiet suburban community with a few aircraft pass-overs, could have the same L_{eq} as a busy urban area where the background level is high while the intrusions over the background are minimal.

L_d is the energy average[1] of the hourly L_{eq} values during the daytime period (7 a.m. to 10 p.m.). In general, the hourly L_{eq} in a community lies within $\pm$ 5 dB(A) of the L_d. The L_{max}, as indicated on the preceding illustration, is the maximum sound level observed during a train pass-by. The duration of the sound at or near the L_{max} level is a function of several factors such as train speed and the distance from the train to the observer. The number of operations per hour, the L_{max} value, and the duration may be combined to obtain the hourly L_{eq} due to BART operations.

The community sound levels are described in terms of the daytime equivalent sound level (L_d). Sound levels associated with BART operations are discussed first in terms of the peak wayside sound level due to a BART train pass-by (L_{max}). The L_{max} values due to individual train pass-bys are subsequently converted to hourly equivalent sound levels (L_{eq}). The L_{eq}'s presented are the sound levels in the wayside communities due to BART.

Acoustic impact is typically predicted on the basis of the magnitude of a given sound and the degree by which that sound exceeds the surrounding community ambient sound levels. In general, the sound levels in the community due to the source being evaluated (in this case the BART system) must exceed the sound levels that would be present without the source before acoustic impact would be expected. This study compares the L_d levels in the community and the L_{eq} levels due to BART. Possibly impacted regions are identified as those regions where the BART L_{eq} levels exceed the community L_d levels. It should be noted that because of large variations within a community, individual locations may or may not have problems, depending on how different they are from the average L_{eq}.

COMMUNITY SOUND LEVELS

The wayside communities along the BART system range from densely-populated residential and residential/commercial areas such as Daly City or Albany-El Cerrito to relatively sparsely-populated (at least for an urban area) residential communities such as may be found near Pleasant Hill, Walnut Creek or Fremont. Adjacent to virtually all of the BART system are other major transportation arteries such as freeways, major urban

[1] The mathematical definition of L_{eq} and L_d may be found on pp. 63-64.

and suburban arterials and railroad tracks. With the exception of the portion of the system near Fremont and Union City, where BART runs near low density residential areas, one of the other major transportation arteries is nearby. Thus, for the most part, BART does not run in regions that would be thought of as "very quiet areas" in its absence.

A recent report prepared for the U. S. Environmental Protection Agency (Galloway et al 1973) indicates that a strong correlation exists between the population density (the number of people per square mile) of an area and the day/night weighted sound level (L_{dn}). The L_d (daytime) levels in communities along the BART system are typically 2-3 dB(A) less than the L_{dn}. Thus, the correlation between population density and L_{dn} may also be used to estimate the L_d.[1]

In a study conducted for the City of San Francisco (Porter et al 1974), it was shown that the L_{dn} (or L_d) values derived from population density information represent somewhat of a mean level in the community. That is, the L_d obtained from population density values is somewhat lower than would be expected on the busiest streets in the community, while somewhat higher than might be expected on the less traveled side streets.

Census values for the population and net residential land area by census tract along the BART system were used in this study to estimate the mean community L_d values. These initial L_d estimates were further refined to account for the proximity of major arterials using the methodology of the previously cited San Francisco report. In essence, the L_d values in regions adjacent to major arterials were raised in proportion to the traffic volume on the arterials. The actual L_d values for the communities along the BART system obtained using population density and traffic volume information will be examined in the following section.

As a means of verifying the L_d values obtained from population density and traffic volume data, the acoustic environment was monitored over a 24-hour period at 12 points along the BART system. The approximate locations of these 12 community measurement sites are shown on Figure 2. Table 1 identifies the L_d for each specific location, as well as giving a brief description of the type of neighborhood in which the sound level measurements were conducted. Figures 3 through 14 illustrate the hourly L_{eq} levels monitored at each site.

[1] L_d rather than Ldn is used in this report because BART currently has no scheduled operations after 8 p.m. The L_d is typically less than the L_{dn} due to the weighting factor of 10 dB which is applied to the nighttime (L_n) levels in the formulation of L_{dn}.

FIGURE 2
COMMUNITY MEASUREMENT SITES

Numbers in boxes refer to location address on Table 1

TABLE 1
SOUND LEVELS AT COMMUNITY MEASUREMENT SITES

Location	Address	Neighborhood Characteristics	L_d in dB(A)
1	832 Liberty Street El Cerrito	Med. High Density Single Family	58
2	664 Spokane Albany	" " "	60
3	Childrens Hospital Oakland	High Density Multi Family	70
4	4153 Hidden Valley Rd. Lafayette	Low Density Single Family (Near Freeway)	59
5	1 Wanda Lane Lafayette	" "	67
6	40 Reata Place Oakland	Medium Density Single Family (Near Freeway)	64
7	35688 Montecito Fremont	Low Density Single Family	54
8	28448 Cole Place Hayward	Medium Density Single Family (Near S. Hayward BART Station)	54
9	1040 San Miguel Concord	Medium Density Single Family (Near Concord BART Yard)	54
10	182 Wayne Court Pleasant Hill	Medium Density Single Family (Near Pleasant Hill BART Station)	55
11	228 Los Olivos Daly City	Med. High Density Single Family (Near Daly City BART Station)	60
12	2219 Humboldt El Cerrito	Med. High Density Single and Multi Family	63

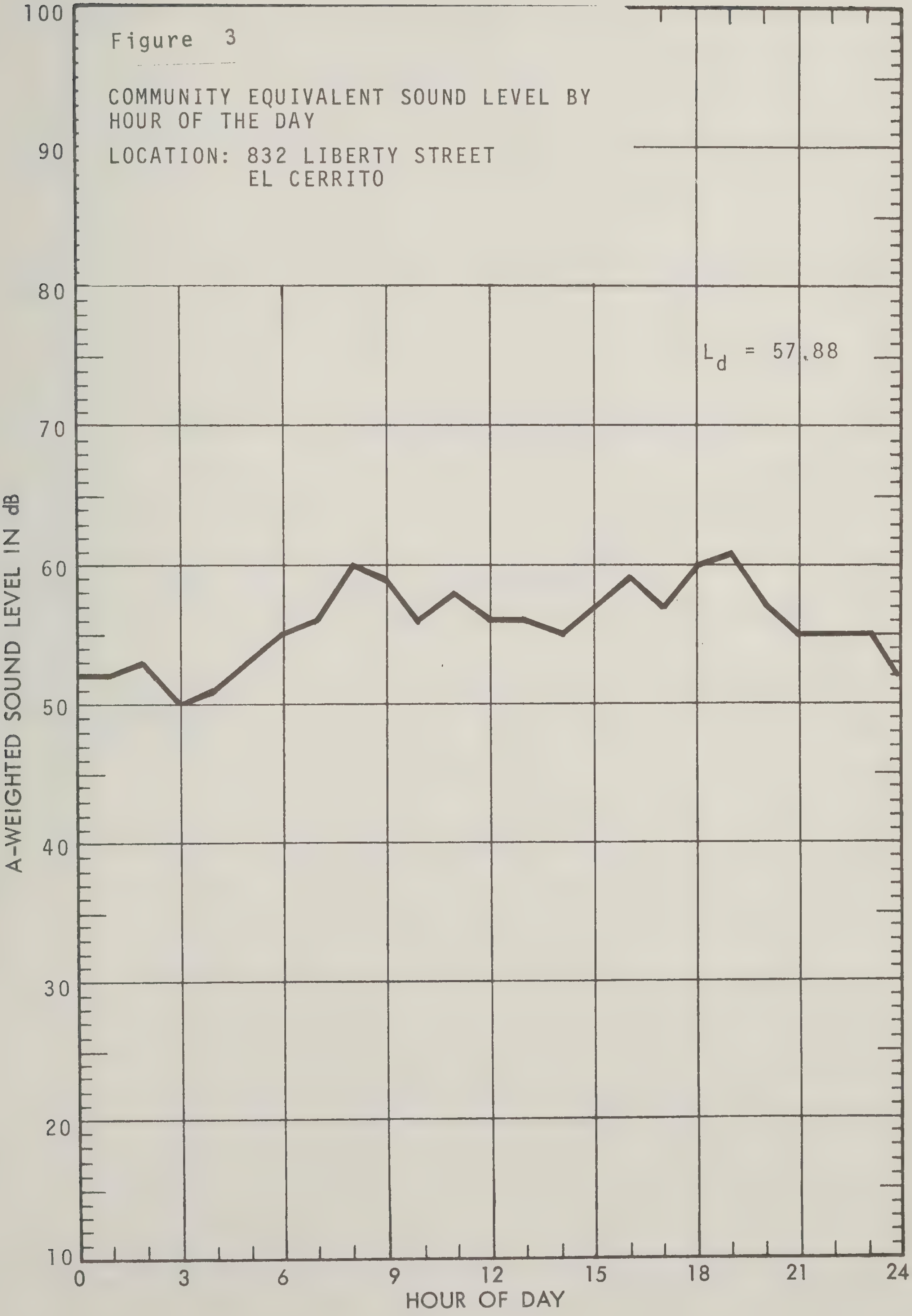


Figure 3
COMMUNITY EQUIVALENT SOUND LEVEL BY HOUR OF THE DAY
LOCATION: 832 LIBERTY STREET EL CERRITO
L_d = 57.88
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

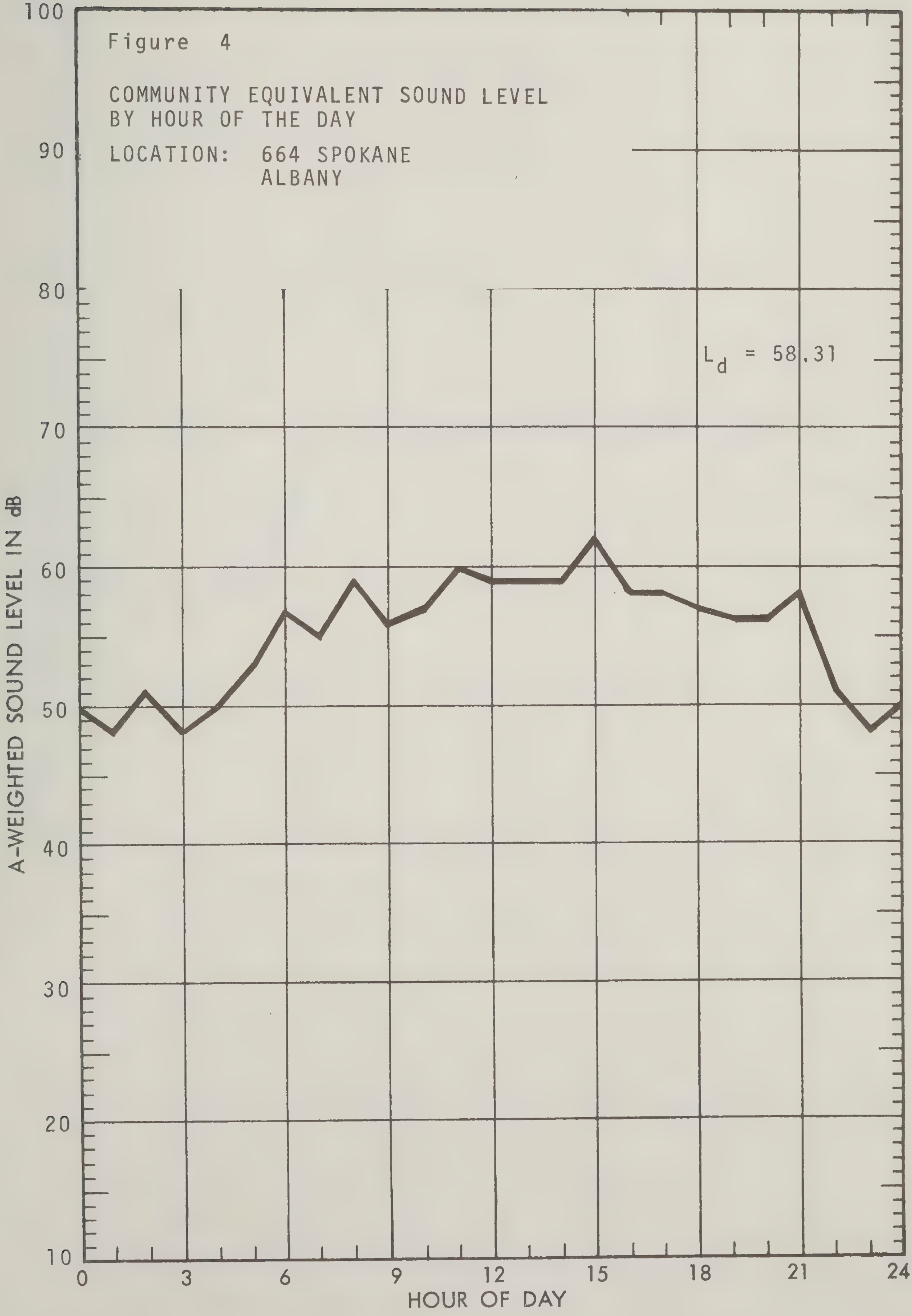


Figure 4
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: 664 SPOKANE
ALBANY
L_d = 58.31
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

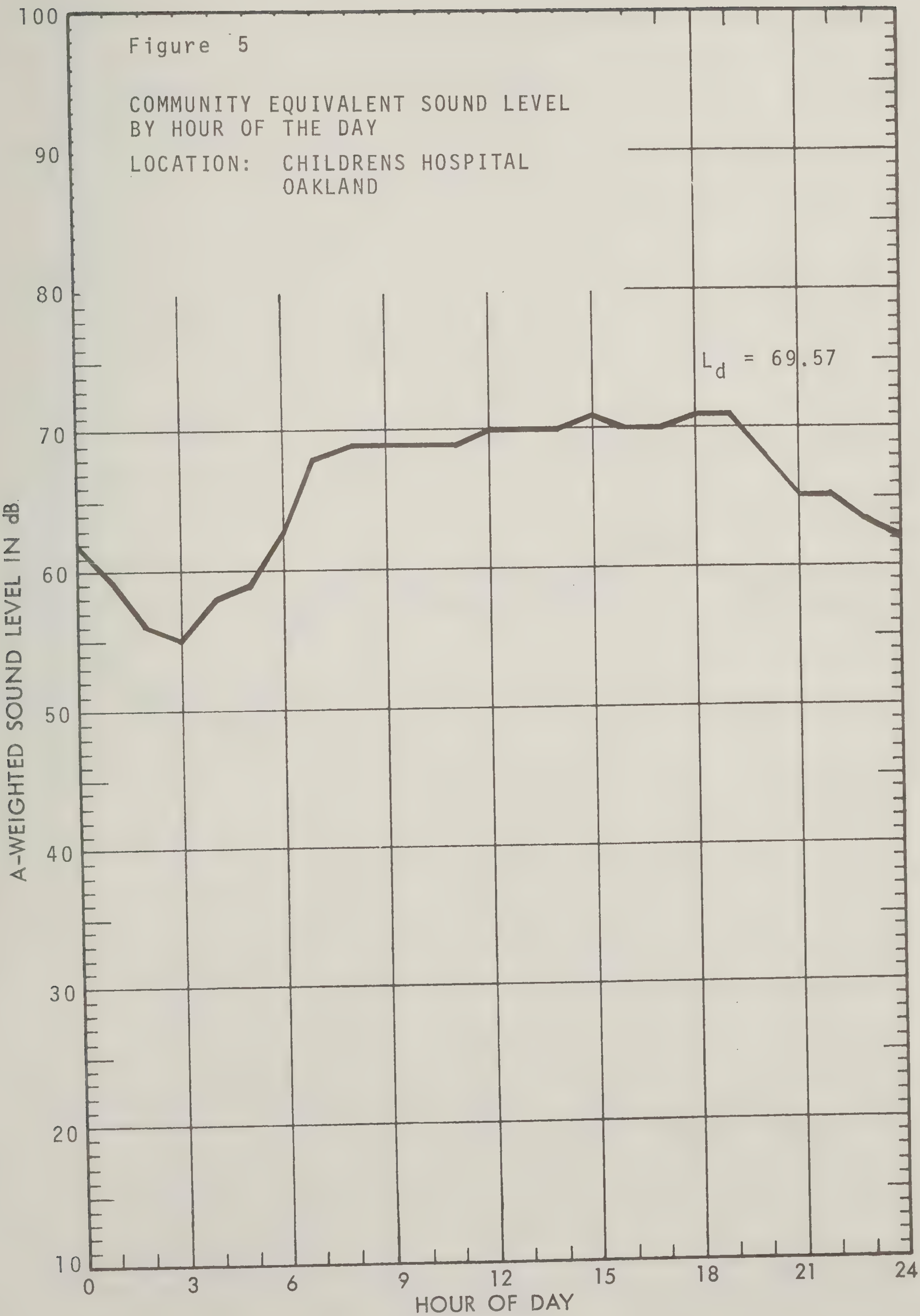


Figure 5
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: CHILDRENS HOSPITAL
OAKLAND
L_d = 69.57
A-WEIGHTED SOUND LEVEL IN dB
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24
HOUR OF DAY

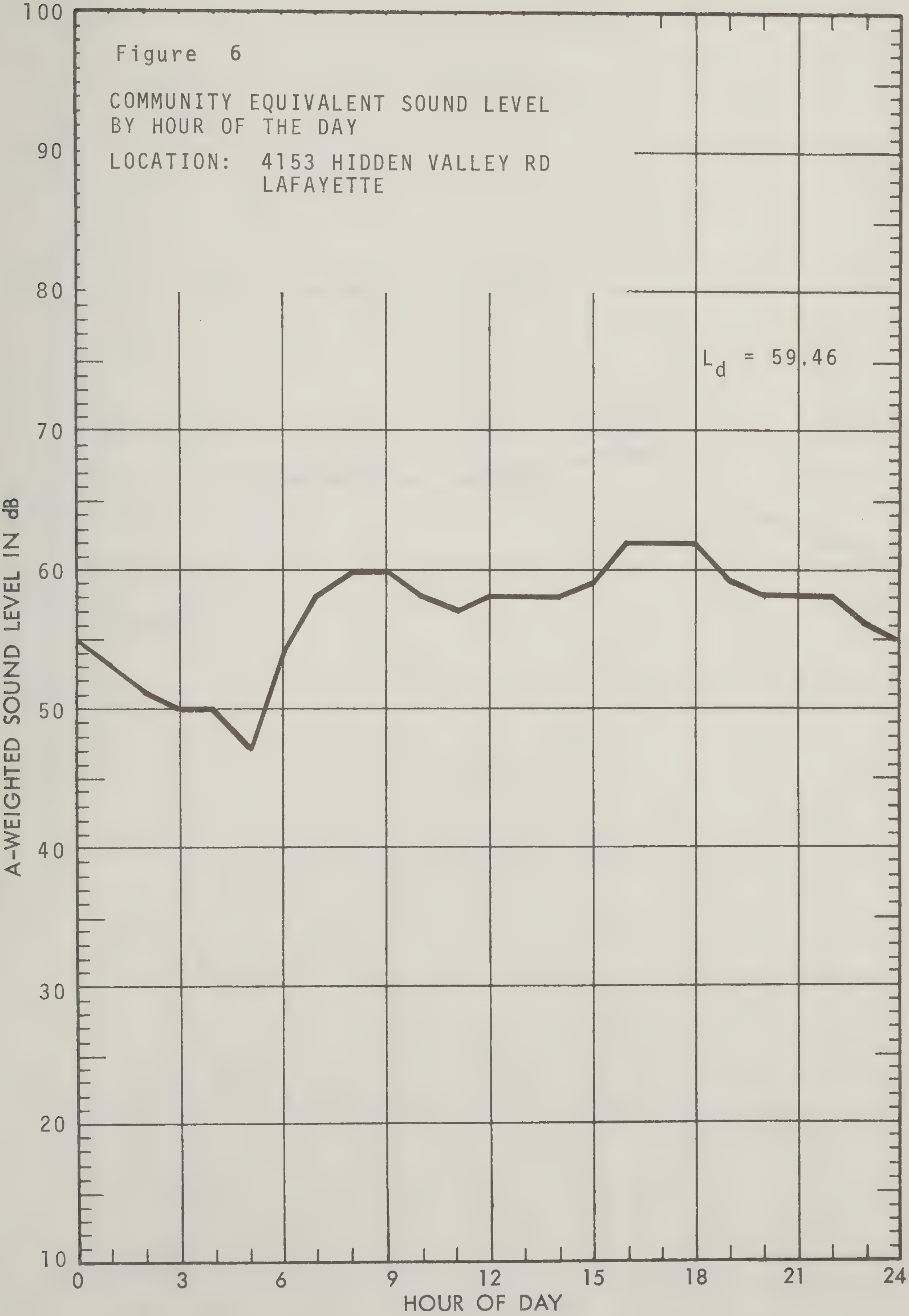


Figure 6
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: 4153 HIDDEN VALLEY RD
LAFAYETTE
L_d = 59.46
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

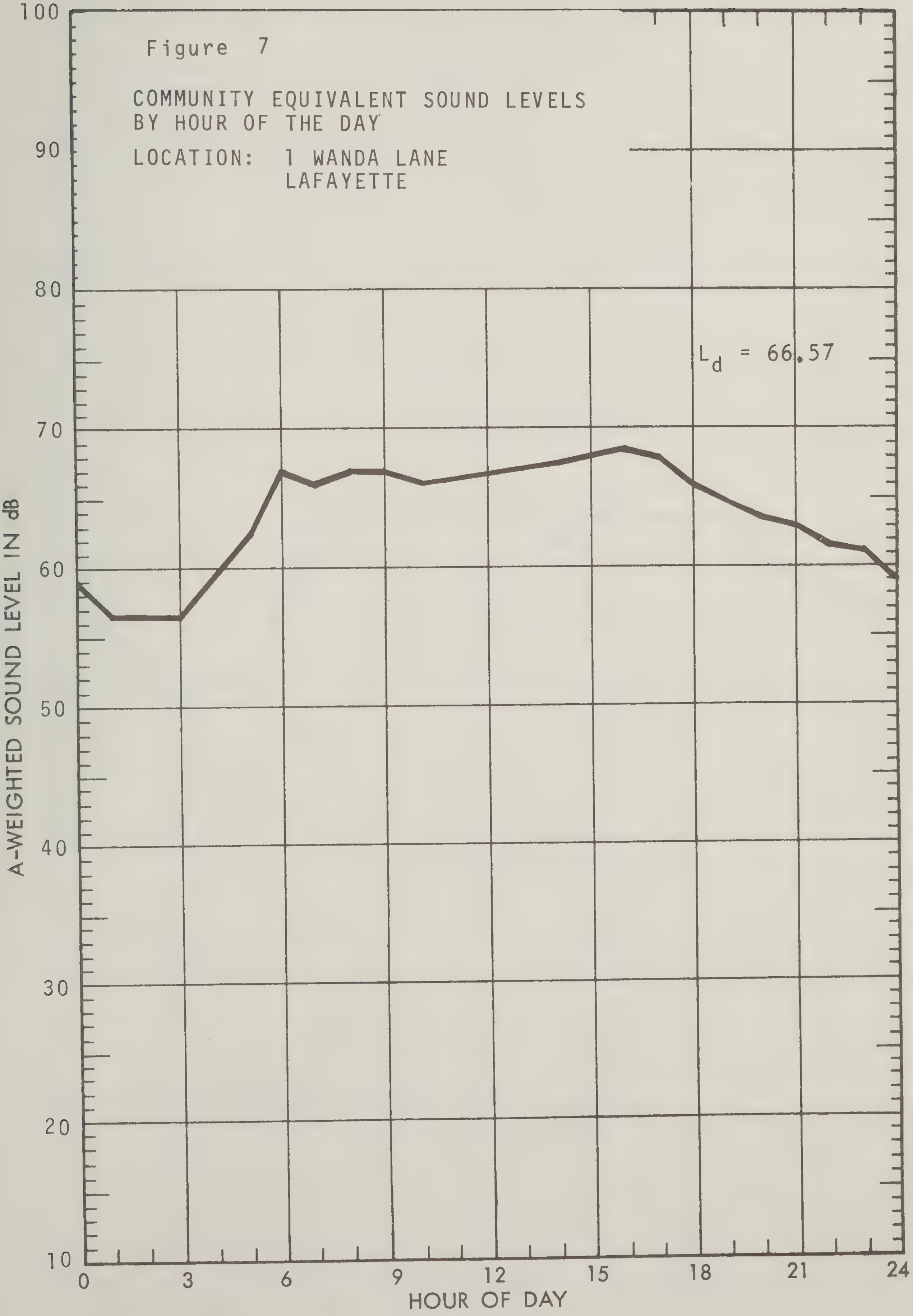


Figure 7
COMMUNITY EQUIVALENT SOUND LEVELS
BY HOUR OF THE DAY
LOCATION: 1 WANDA LANE
LAFAYETTE
L_d = 66.57
A-WEIGHTED SOUND LEVEL IN dB
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24
HOUR OF DAY

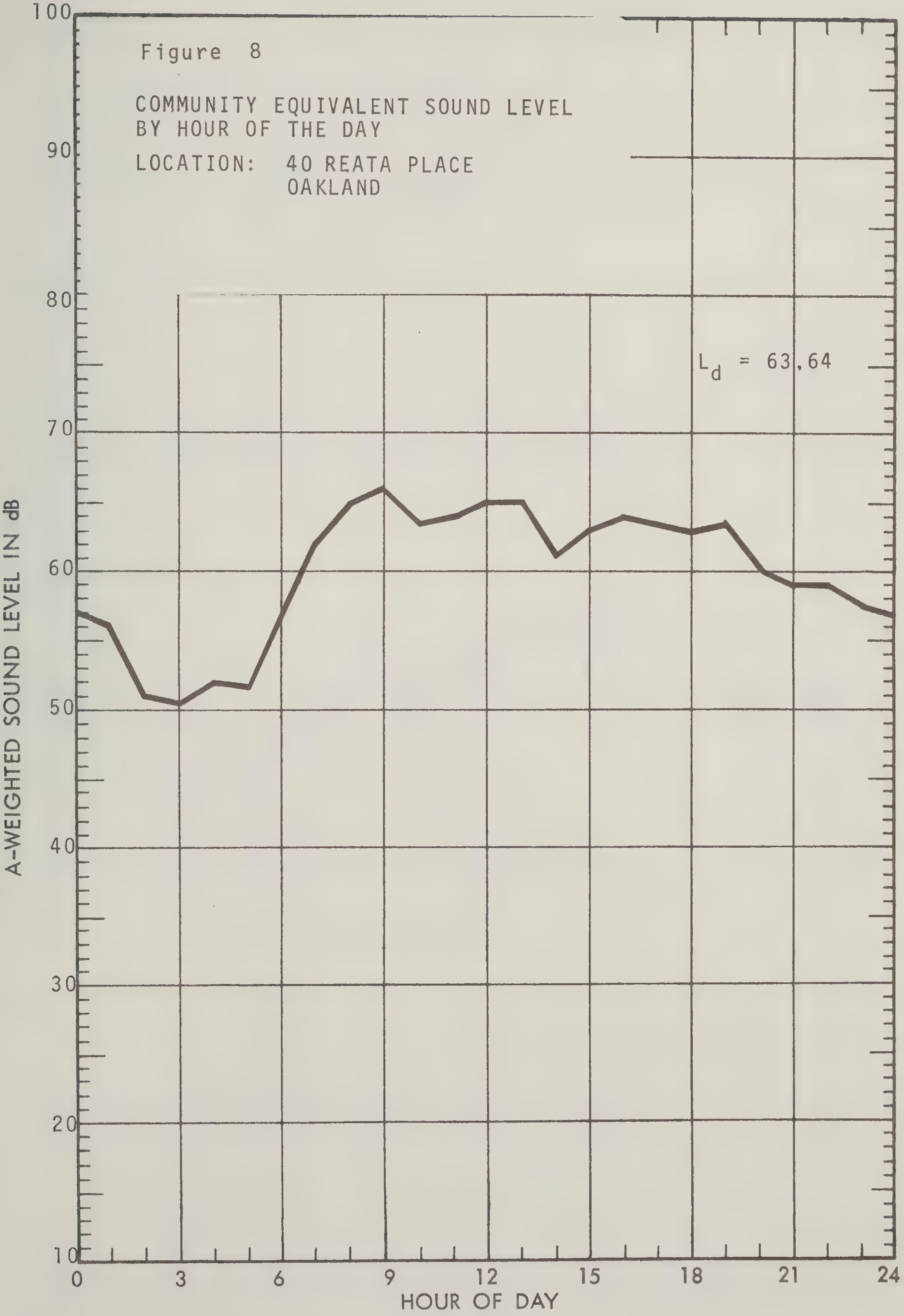


Figure 8
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: 40 REATA PLACE
OAKLAND
L_d = 63.64
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

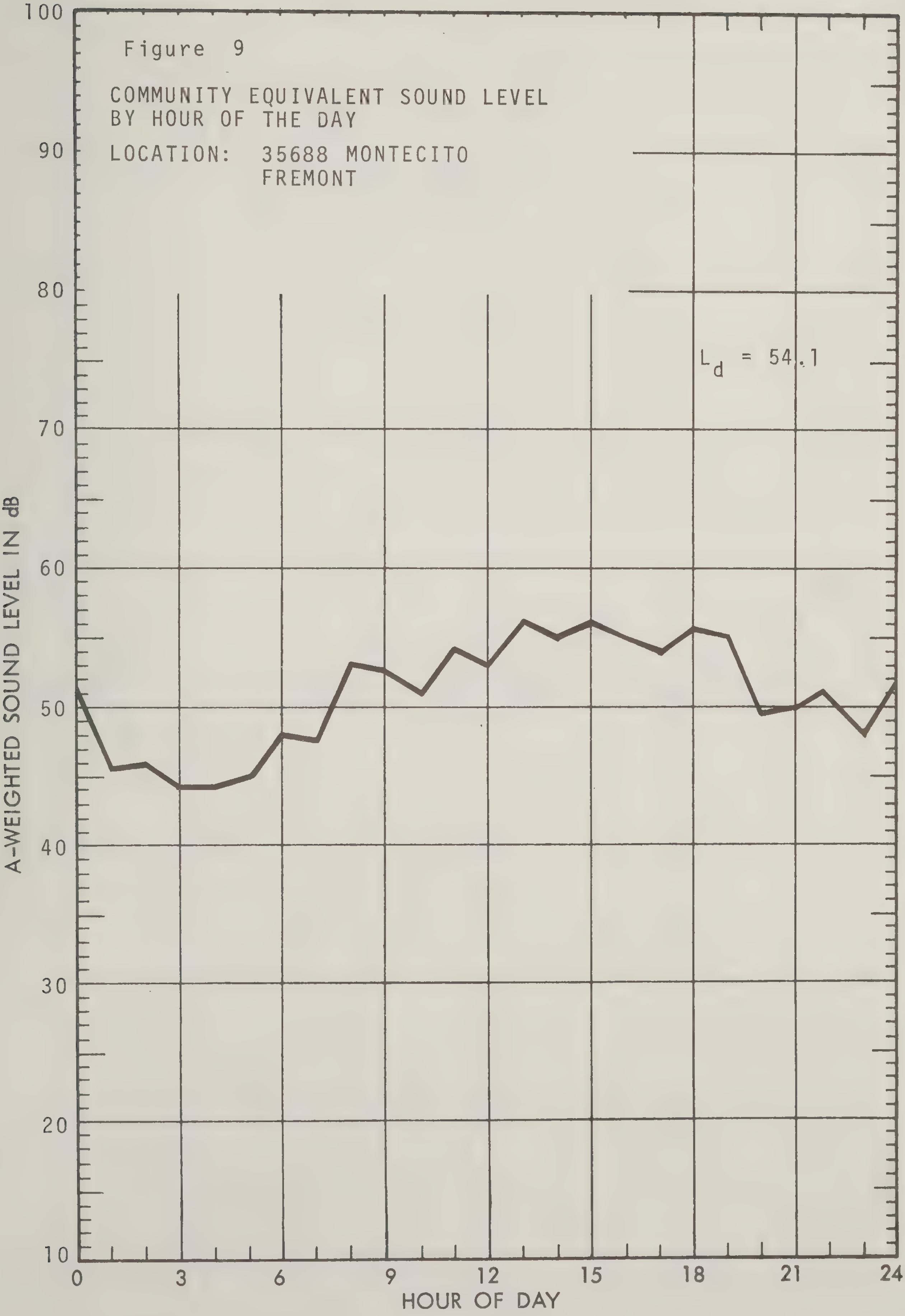


Figure 9
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: 35688 MONTECITO
FREMONT
L_d = 54.1
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

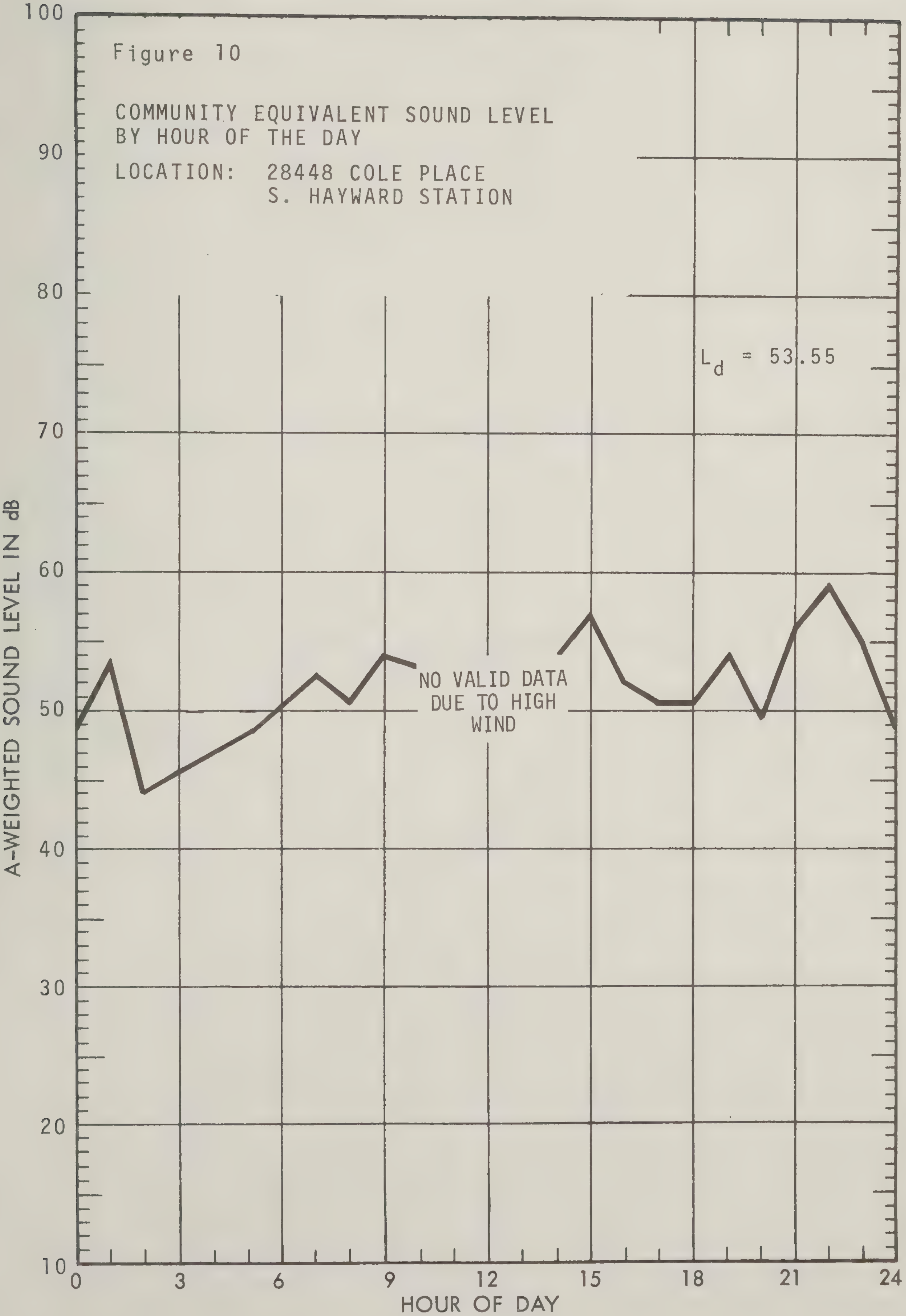


Figure 10
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: 28448 COLE PLACE
S. HAYWARD STATION
L_d = 53.55
NO VALID DATA
DUE TO HIGH
WIND
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

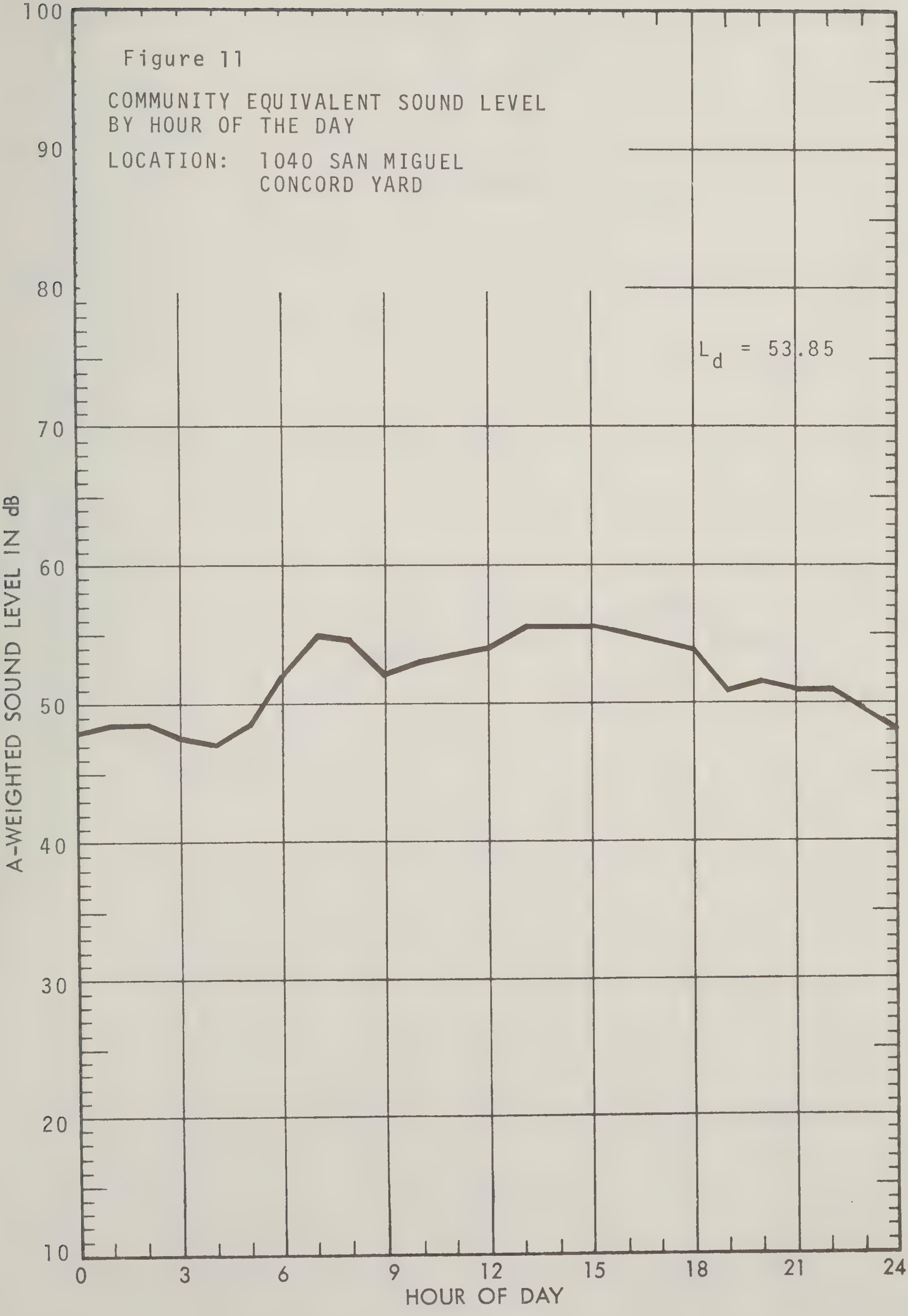


Figure 11
COMMUNITY EQUIVALENT SOUND LEVEL BY HOUR OF THE DAY
LOCATION: 1040 SAN MIGUEL CONCORD YARD
L_d = 53.85
A-WEIGHTED SOUND LEVEL IN dB
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24
HOUR OF DAY

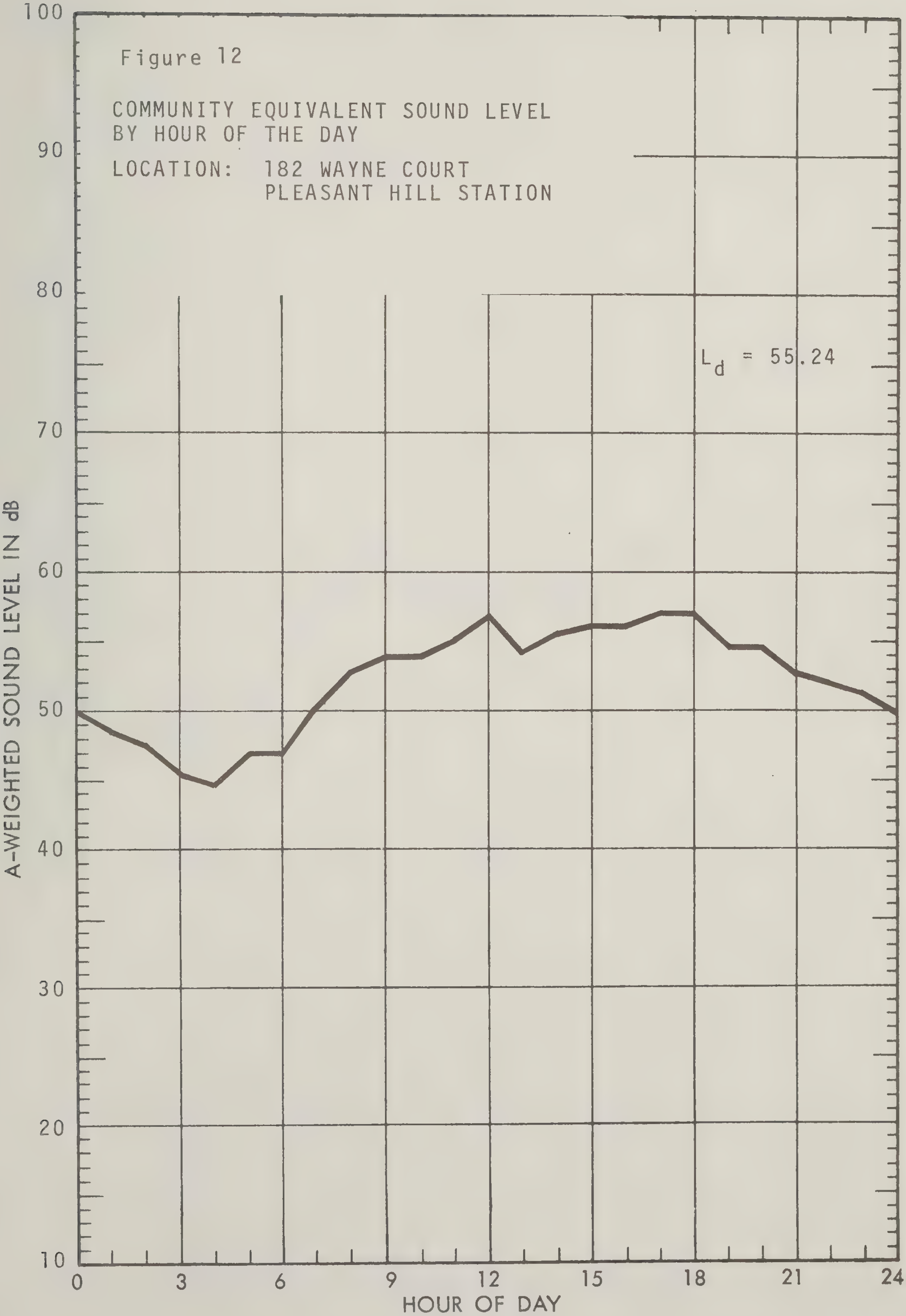


Figure 12
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: 182 WAYNE COURT
PLEASANT HILL STATION
L d = 55.24
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

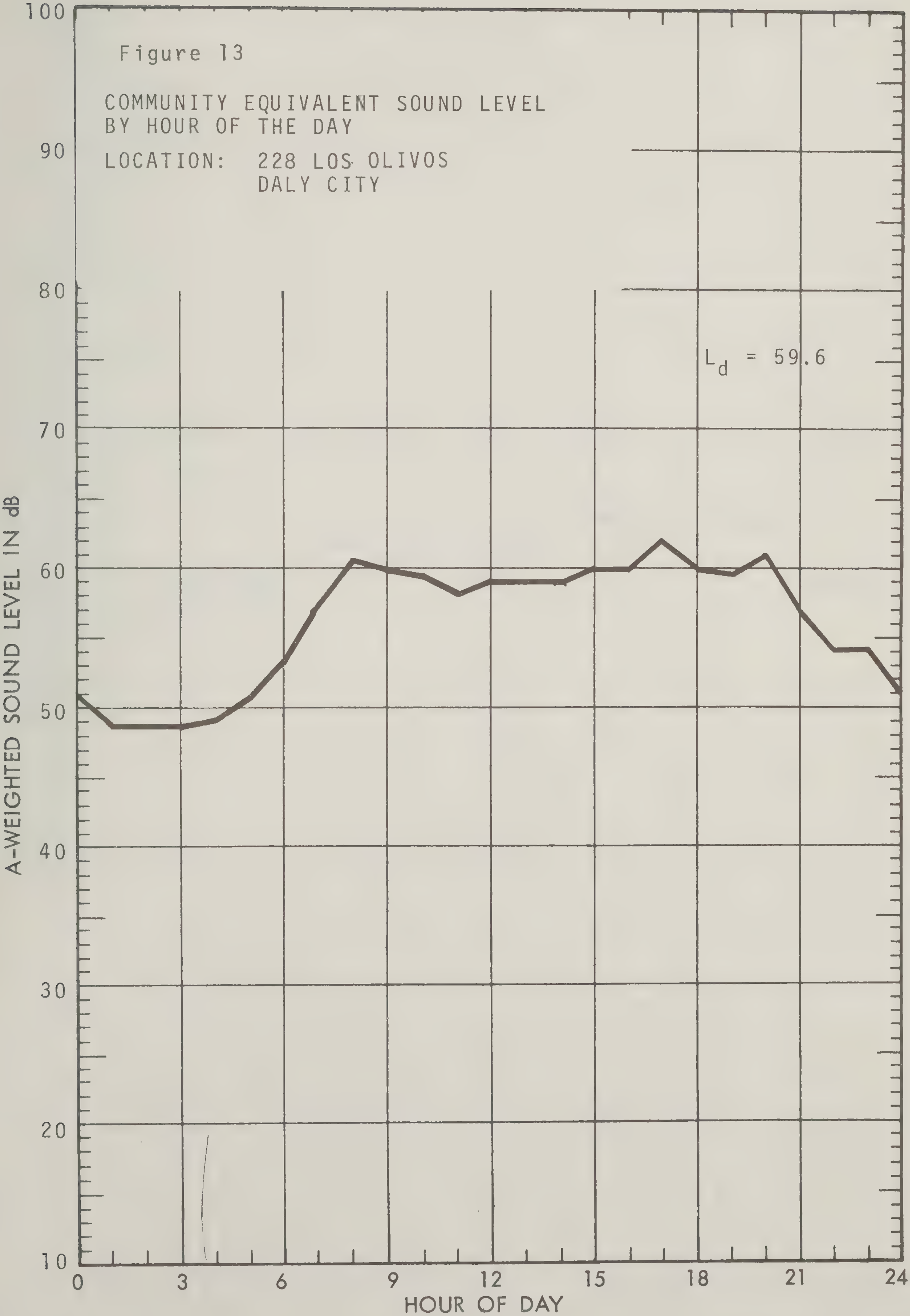


Figure 13
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: 228 LOS OLIVOS
DALY CITY
L_d = 59.6
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

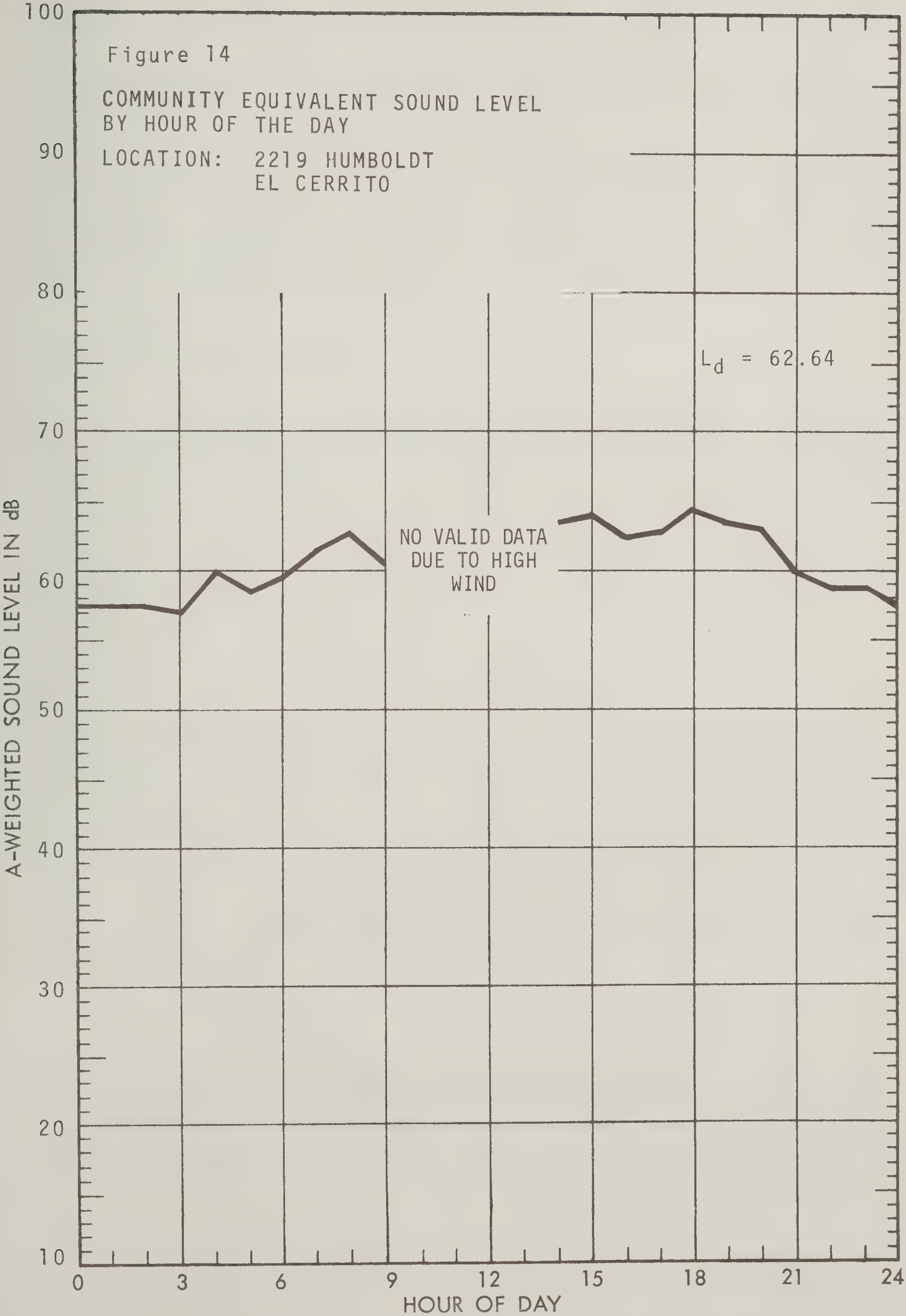


Figure 14
COMMUNITY EQUIVALENT SOUND LEVEL
BY HOUR OF THE DAY
LOCATION: 2219 HUMBOLDT
EL CERRITO
L_d = 62.64
NO VALID DATA
DUE TO HIGH
WIND
A-WEIGHTED SOUND LEVEL IN dB
HOUR OF DAY
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24

The range of L_d values actually measured in communities along the BART system, as may be seen from Table 1, was approximately 55 to 70 dB(A). This range is the same as was determined from the census and traffic volume information. A conclusion drawn from the study of sound levels in the vicinity of the BART systems is that an L_d of 55 dB(A) appears to be a lower limiting value. This lower limit on the daytime equivalent sound level represents the composite background sound from the various transportation noise sources near and far which serve the Bay Area. Since BART is, after all, an urban mass transit vehicle, it is not altogether surprising that transportation-generated sounds dominate the acoustic environment everywhere along the BART system.

BART SYSTEM SOUND LEVELS

This section will identify the basic character and magnitude of sound levels generated by the BART system in the surrounding community. The first portion will discuss various factors such as speed, type of roadbed, individual vehicle conditions, and distance from the BART line as they affect the wayside sound levels. In the second portion, the actual magnitude of the levels observed at the wayside for various configurations will be reviewed. The final portion of this section will illustrate the relationship between the magnitude of sounds generated by BART and the equivalent sound levels that are observed in the community.

Primary Factors Affecting Wayside Sound Levels

There are many factors which affect the magnitude of wayside sound levels observed along the BART system. During the course of this study, several of the factors have been identified as having a more significant effect on the observed levels than others. Three of these primary factors, train speed, track configuration and vehicle condition relate to the amount of sound actually produced by BART operations. Distance from the track and shielding, on the other hand, relate to the path by which BART sounds are transmitted from the source to the receiver. The combined effect due to both types of factors must be considered in the evaluation of BART-generated sounds at any particular point.

Train Speed

The individual factor with the greatest effect on the wayside sound levels along the BART system is train speed. Numerous studies (e.g., Manning et al, 1973) concerning the sound levels generated by steel-wheeled rail vehicles have shown that the sound energy generated varies with approximately

the cube of the vehicle speed. Through a series of measurements consisting of monitoring sound levels on-board individual BART cars as they traveled over the entire 71-mile length of the system, this dependence has been verified for the BART system. The methodology section of this report outlines the procedure used to establish a relationship between the on-board measured sound levels and wayside sound levels.

Using sound levels monitored on-board a limited number of cars traversing the entire BART system, a series of speed versus sound level data points were obtained. A subsequent regression on the sound level versus speed data revealed that the sound level varied as 28 times the common logarithm of the speed. The specific relationships determined from the regression analysis may be expressed as:

Tie-and-Ballast Track

$$L_p \doteq 29 + 28 \log_{10} S \ \text{dB(A)} \qquad \text{Equation (1)}$$

Aerial Track

$$L_p = 30.5 + 28 \log_{10} S \ \text{dB(A)} \qquad \text{Equation (2)}$$

Where: L_p = On-board sound level in dB(A)

S = Train speed in miles per hour

Since the sound power level and thus sound level are proportional to 10 times the common logarithm of the sound energy, the measured results from BART are in close agreement with the results of previously cited studies.[1]

Using the 28 $\log_{10}$ relationship, the wayside sound levels rise approximately 8 dB(A) between the speeds of 40 and 80 mph. As an example, a train travelling 40 mph on tie-and-ballast track would generate a wayside sound level of 75.5 dB(A); at 80 mph the expected level would be 84 dB(A).

---

[1] No statistically significant difference between the 28 $\log_{10}$ relationship reported here and the 30 $\log_{10}$ often cited elsewhere is implied. Indeed, over the typical range of BART train speeds (36 to 80 mph) the difference between the sound levels computed using the two relationships is less than 1.0 dB.

Track Configuration

Using the relationship between wayside and on-board sound levels and the 28 $\log_{10}$ speed dependence previously discussed to normalize the data, the on-board measurements were used as a means of rough screening or grading the variation in sound level from point-to-point throughout the entire BART system. Since measuring the BART-generated sound levels throughout the 71-mile system was obviously an impractical procedure, this knowledge of the way the sound levels varied from point-to-point throughout the system was quite important in choosing specific wayside measurement sites.

The mean on-board sound levels (when normalized to a constant speed) exhibited little variation (the standard deviation was approximately 1 dBA) between sections of similar track type on the BART system. Significant differences, however, were observed between different types of track configuration. Specifically, the on-board and wayside measurements indicated a consistent 5 dB(A) difference between the sound levels generated by vehicles on tie-and-ballast track and those on track on aerial structures. In every case, the track on aerial structure generated the higher wayside sound levels.

Vehicle Condition

No detailed information concerning the effect of various maintenance procedures on individual BART vehicles was determined during this study. Although an examination of the effect of aging between the initiation and completion of this program was identified as one of the desirable goals, the necessary scheduling of such tests proved to be incompatible with the basic program schedule. However, a baseline useful for future measurements to determine the effect of aging and maintenance has been established.

The standard deviation of the sound levels of individual trains passing a wayside observation point about the mean level for all trains at the same speed is approximately 1.5 dB. Assuming that the distribution of individual train sound levels about the mean is approximately normal, this variance indicates that some 90% of the vehicles would produce sound levels within ± 3.0 dB of the mean. A repeat measurement at one or more of the wayside measurement locations used for this program at some later date (tentatively planned for the Phase II study program) will provide information concerning the effect of aging and maintenance. Should the variance increase significantly while the mean remains constant, a non-uniformity in vehicle maintenance might be indicated. On the other hand, if the standard deviation between cars remains at approximately 1.5 dB while the mean increases, a general aging of all vehicles rather than lack of attention to a few individual vehicles might be indicated. These and other such hypotheses will be tested during the Phase II program.

Distance and Shielding

A recent Department of Transportation report (Remington et al, 1974) presented a mathematical model of rapid transit vehicle sound propagation. This model considers the sound generated on a transit line to be equivalent to a line of uncorrelated point sources. In order to verify the applicability of this model to the BART system, a series of simultaneous measurements at two distances from both tie-and-ballast and aerial track was conducted. When the data from this series of measurements were normalized using Equation (3) below (adapted from the referenced report) to a distance of 50 ft. from the centerline of the track and a 6-car train, the standard deviation of the difference between measurements was less than 1 dB. Thus, the uncorrelated point source model may be used to normalize measurements taken at varying distances from the BART line to a standard distance.

EQUATION (3)

$$\Delta L = 10 \log_{10} \left[\frac{34.4}{d} \times \tan^{-1} \left(\frac{35N}{d} \right) \right] \text{ dB(A)}$$

Where: ΔL = Difference between measured level and the normalized level of a 6 car train at a distance of 50 feet

d = Perpendicular distance from measurement point to the train in feet

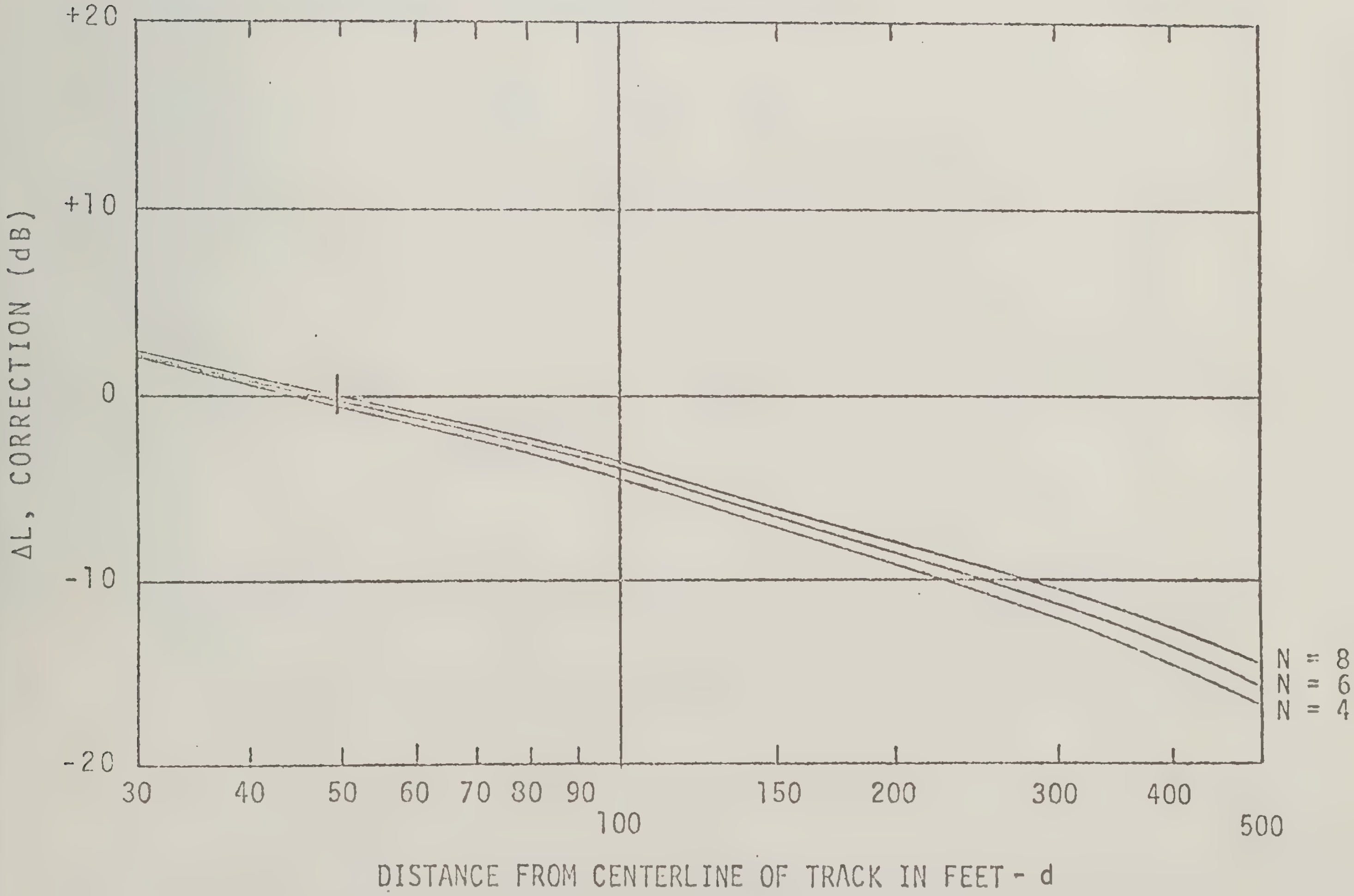
N = Number of cars in train

A graph of Equation (3) is presented on Figure 15. This Figure was used to normalize all data obtained during the measurement program to a standard distance of 50 feet from the centerline of the track and a 6-car train.

The first row of houses or other buildings adjacent to the BART line tends to shield those residences further removed from the system from BART-generated sounds. Using the estimates provided in a recent review of barrier attenuation information (Kurze, 1974), the shielding offered by the first row of structures would be expected to be on the order of 5 to 10 dB. Where the houses are fairly close together (as is typical in the Bay Area), the degree of shielding would tend to be nearer the 10 dB value than the 5 dB value.

FIGURE 15

PLOT USED TO NORMALIZE TRAIN PASS-BY DATA



Measured Wayside Sound Levels

Wayside measurements of BART-generated sounds were conducted at 15 locations along the BART system (Figure 16). The purpose of these measurements was to determine the magnitude of the sounds generated by BART which propagate to the surrounding community. The maximum sound level caused by a BART vehicle pass-by (L_{max}) was the term chosen to describe the magnitude of BART sounds. The following paragraphs summarize the results of the wayside measurements for various system configurations.

Track on Tie-and-Ballast

The sound levels generated by approximately 100 pass-bys of BART trains running on tie-and-ballast track were recorded at four wayside locations. During these pass-bys, train speeds ranged from approximately 36 to 80 mph. Using the mean of the measured L_{max} levels (normalized to 50 feet and a 6-car train) and the 28 $\log_{10}$ of speed relationship, the mean wayside L_{max} level at a distance of 50 feet from the centerline of the track for trains at 80 mph was found to be 84 dB(A).

As a means of observing the variation in the L_{max} levels generated by individual trains, the measured levels were normalized to a speed of 80 mph using the previously determined 28 $\log_{10}$ speed relationship. The variance of the individually measured L_{max} levels about this normalized mean was taken to be primarily attributable to the differences between vehicles.[1] Analysis of the tie-and-ballast wayside data revealed that the standard deviation of the L_{max} levels about the mean was approximately 1.5 dB. Thus, assuming a normal distribution, the wayside L_{max} level generated by 90% of the BART trains on tie-and-ballast track would be expected to lie within $\pm$ 2.5 dB of the measured mean level. This mean level is indicated on Figure 17 as a function of train speed.

Track on Aerial Structure

The sound levels generated by approximately 100 BART vehicle pass-bys ranging from 36 to 80 mph were monitored at the wayside adjacent to BART tracks on aerial structures. As with the monitoring of train pass-bys on tie-and-ballast track, the L_{max} level and train speed were determined for each pass-by.

[1] Contributions to this variance are also made by the errors of estimate of both the distance normalization equation and the speed regression equation.

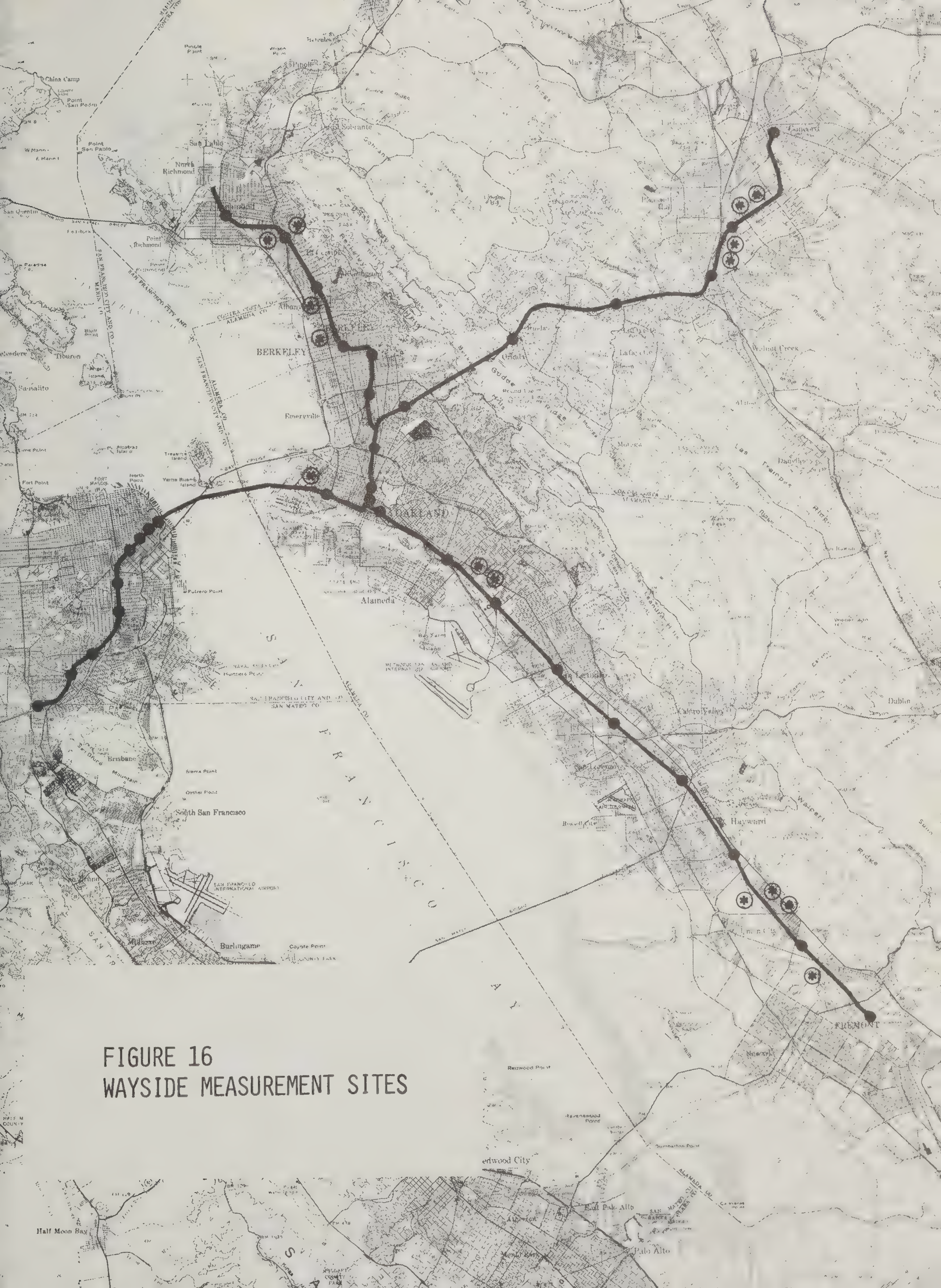
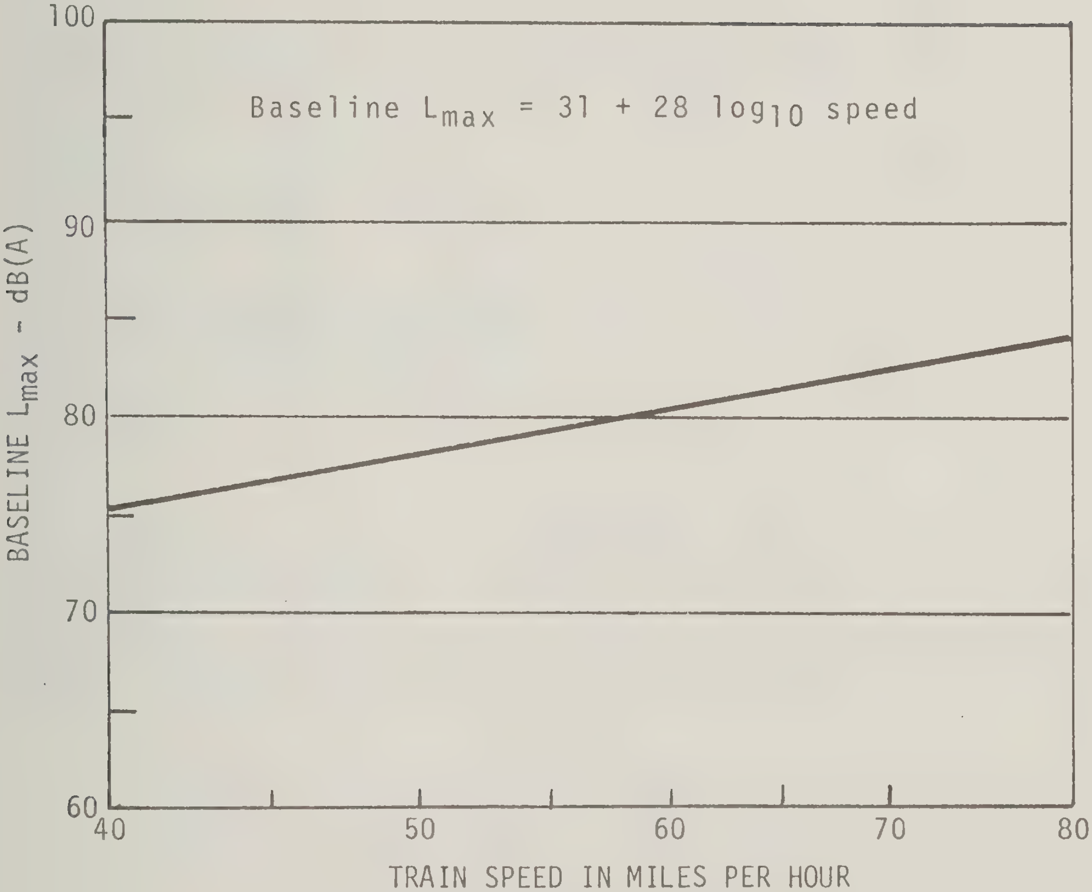


FIGURE 16
WAYSIDE MEASUREMENT SITES

Figure 17

BART MAXIMUM SOUND LEVEL (L_{max})*
AS A FUNCTION OF TRAIN SPEED



EXAMPLE: Six car train travelling 65 mph on aerial structure crossing over a switch.

L_{max} = 82 + 5 + 5 = 92 dB(A)

ADDITIONS TO BASELINE L_{max}

CONDITION	dB(A)
Tie & Ballast (Berm or Grade)	+0
Aerial Structure	+5
Switch	+5
Curve (Radius < 4500')	+5

* Normalized to a 6 car train and a distance of 50' from centerline of track

Using the mean of the data obtained from the wayside measurements and the 28 $\log_{10}$ speed relationship, the mean wayside L_{max} level at a distance of 50 feet from the track for trains on aerial structures was found to be 89 dB(A) for a train traveling at 80 mph. This level is 5 dB higher than was determined for trains operating on tie-and-ballast track at the same speed.

The standard deviation of the measured sound levels about the mean was found to be approximately 1.8 dB. This variance was attributed to the mechanical differences existing between various vehicles. Thus, assuming a normal distribution, some 90% of the trains on aerial structures would be expected to generate wayside sound levels within $\pm$ 3 dB of the mean level. This mean L_{max} is indicated on Figure 17.

By way of comparison, many of the present fleet of buses operated by the San Francisco Municipal Railway District and the noisier of over-the-road heavy-duty trucks generate peak wayside sound levels in the 85-90 dB(A) region at a distance of 50 feet.

Switches

Switches or crossovers used for diverting trains and cars from one track line to another on the BART system represent the major discontinuities in the continuous welded, smoothly ground, BART rail system. As the BART vehicle wheels pass over the gap in the rail system caused by these switches, metal-to-metal impacts occur. Part of the energy associated with these impacts is radiated to the surrounding community in the form of noise.

Measurements at the wayside in the vicinity of switches have shown that, as the vehicles cross over switches, the sound levels are approximately 5 dB higher than the sound levels normally associated with trains running on smooth track. This 5 dB increase is essentially independent of speed. For example, the mean sound level at a distance of 50 feet from the train running on smooth tie-and-ballast track is approximately 84 dB(A) at 80 mph. As the train is crossing over a switch, the expected sound level would be 89 dB(A).

Although the increase in the peak wayside level due to a switch on tie-and-ballast track is of the same magnitude as the increase due to a switch on aerial track, there is a major difference in the character of the sound between the two situations.

When the switch is located on tie-and-ballast track on berm, the sound levels rise very briefly as the individual trucks (wheel sets) on each car cross the switch. The sound levels then fall back to a level normal for tie-and-ballast track until the next truck hits the switch as shown to the left in Figure 18.

FIGURE 18
TIME HISTORIES OF BART TRAIN CROSSING TYPICAL SWITCHES

As may be seen, the wayside sound level adjacent to a switch on a berm or grade has somewhat of a notched or saw-tooth pattern over time.

For switches located on aerial structures, however, the decrease in sound level between trucks passing over the switch was not nearly so evident. As the right-hand illustration above indicates, the decrease in sound level between trucks hitting the switches tends to be on the order of 1-2 dB--if present at all. Since the total amount of sound energy radiated to the community is proportional to the area under time-history curves such as those shown above, it follows that switches on aerial structures radiate more sound energy to the surrounding communities. A more exact relationship between the relative amounts of sound energy radiated to the community for switches on berm or aerial structures will be presented in a later section. The effect of switches on the wayside L_{max} levels is indicated on Figure 17.

Curves

There is considerable discussion in the literature concerning the noise generated by steel wheeled rail vehicles as they negotiate short radius curves. Among the variables controlling the wayside sound levels in the vicinity of the curves are the radius of the curve itself and the vehicle speed. During this program, the wayside sound levels for 70 BART vehicle pass-bys were monitored adjacent to curves on aerial structures (measurements were conducted both inside and outside of the curve radius). While an increase of sound level as trains negotiated such curves was observed, no conclusive relationship between train speed and curve radius and wayside sound level was determined.

The median sound levels observed adjacent to curves with a radius of less than 4500 feet tend to be approximately 5 dB higher than would be expected at the wayside of a vehicle operating on straight track. Since this tendency was noted only for approximately half of the vehicles observed (no correlation was found between vehicle speed and the vehicles exhibiting higher sound levels), these findings must be considered, at best, tentative. Furthermore,

the increased sound levels were observed adjacent to several portions of curved track where the radius was considerably in excess of 4500 feet. Additional study, perhaps in the Phase II program, of the precise relationship between train speed, radius of curvature and noise level would provide additional information pertinent to the design of new systems. Additionally, from subjective observation it appears that a factor accounting for the acceleration or deceleration of the train through the curve may also affect wayside sound levels. The knowledge of how these variables are interrelated would be of great benefit in the design of future systems.

Tunnel Entrances and Exits

Approximately 60 individual measurements of BART train pass-bys were obtained in the vicinity of the North Berkeley BART tunnel entrance. No significant increase in the maximum level created by BART pass-bys was observed at this location. There was, however, an effect attributable to the tunnel on the duration of the sound level generated by the BART pass-by. The wayside sound levels in the vicinity of the tunnel entrance remained within 10 dB of the maximum level approximately twice as long (e.g., 12 seconds vs. 6 seconds) as would be expected adjacent to normal elevated or tie-and-ballast track. This fact is due to the reverberation of sound within the tunnel and subsequent release of this sound energy to the atmosphere at the tunnel entrance.

Thus, while the maximum wayside sound level does not appear to be affected by the tunnel, the duration of the sound within 10 dB of its maximum is markedly affected. The increase in the amount of time which the sound level remains within 10 dB of its maximum directly affects the equivalent sound levels produced by BART trains as they pass the observation position. Thus, due to the increase (approximately 2-5 dB) in the equivalent sound level generated by the trains, some increase in the subjective awareness of people to BART vehicles in the vicinity of tunnel entrances and exits might be expected.

Station Area Sound Levels

Sounds created by automobiles and the feeder bus system entering and departing from BART stations were considered as a possible source of impact in the community at the beginning of this program. During the course of the program, measurements were conducted in the vicinity of several BART stations (South Hayward and Pleasant Hill in particular) to determine the effect of automobile and feeder bus traffic in and out of the station. In general, it was found that the sound levels generated by

automobile traffic into and out of the stations were virtually lost in the background of other vehicular operations in the community. Traffic studies conducted for other portions of the BART impact analysis program have indicated that automobile traffic into and out of BART stations comprises at most 30% of the traffic on surrounding streets. Since increased sound level is proportional to the logarithm of increased traffic, BART traffic would be expected to increase the ambient sound around the stations a maximum of 1 dB. The measurements conducted near the stations indicated that indeed negligible increase in sound level due to BART-induced automobile traffic was observed.

As a means of evaluating the effect of BART feeder bus traffic on the community sound levels adjacent to BART stations, the maximum wayside sound levels were measured for approximately 60 AC Transit vehicles operating under accelerating conditions. The data obtained from these measurements indicated that AC Transit vehicles produced nearly the same wayside sound levels as do Golden Gate Transit vehicles. Using a wayside sound level nomograph developed for Golden Gate Transit vehicles (Porter and Schwartz 1974), the hourly equivalent wayside sound levels at a distance of 50 feet from the centerline of a street carrying 30 such buses per hour (the greatest bus volume is currently 27 buses per hour) was found to be 66 dB(A). In general, this level is less than or equal to sound levels already present on the arterials near BART stations due to other transportation sources.

Wayside Equivalent Sound Levels

In the preceding section, the maximum A-weighted sound levels observed at the wayside due to BART pass-bys under various conditions were examined. Since this maximum level is observed only during a short period during the actual pass-by and cannot be considered constant over the period of an hour or a day, it cannot be compared directly with the community equivalent sound level previously identified. Using the maximum A-weighted sound level, the duration of the individual event and the number of events per hour , an hourly equivalent sound level for BART pass-bys may be computed.

When observed at the wayside, the time-history of a BART pass-by increases in the sound level up to some plateau of maximum sound level as the train arrives directly in front of the observer. This sound level tends to remain constant or nearly constant at this plateau level as the train passes in front of the observer position and then gradually decrease until the background sound level is achieved. The time-history for an actual BART train pass-by is illustrated in Figure 19 on the left hand side of the diagram.

FIGURE 19
ACTUAL AND IDEALIZED TIME HISTORIES OF A BART TRAIN PASS-BY

The right hand portion of the example above illustrates an idealized or smooth time-history pattern. If L_{max} is the plateau height, N is the number of operations per hour, S is the vehicle speed in mph, A is the number of cars on the train, and D is the distance from observer to the centerline of the track, then the hourly equivalent sound level at the wayside may be calculated using the following equation:

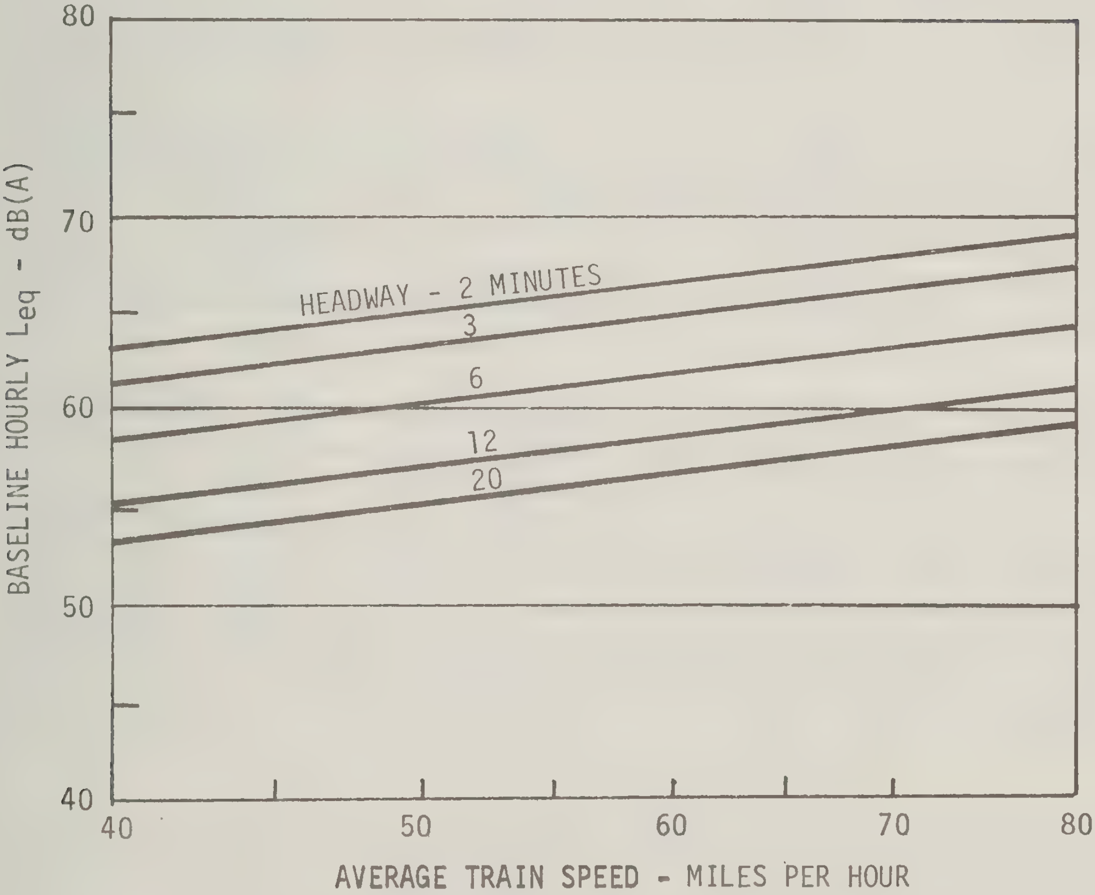
$$L_{eq} = L_{max} + 10 \log_{10} \left[\frac{N}{SD} \right] + 10 \log \left[\frac{70A + 10 + 3.46\,D}{146} \right] \qquad \text{EQUATION (4)}$$

Equation (4) will yield hourly L_{eq} levels due to BART pass-bys that agree with field test results provided that $D < 500$ feet and that there is clear line-of-sight from the observer to the BART system. At distances greater that 500 feet, because of air and ground attenuation, the observed sound level is usually lower than that predicted by Equation (4). Additionally, a row of single-family houses between the observer and BART line tend to reduce the L_{max} and L_{eq} levels by approximately 10 dB.

The L_{max} or plateau height in Equation (4) may be obtained from Figure 17 if the train speed and track configuration are known. Combining the information from Figure 17 and Equation (4), Figure 20 illustrates the relationship between the equivalent sound level at a distance of 50 feet from the centerline of the track for various track configurations. It will be noted that different L_{eq} values will be observed at the wayside for different frequencies of train operation. Additionally, it should be noted that a correction factor must be applied to the levels obtained from Figure 20 to account for track type, train length and the effect of switches and curves.

Figure 20

BART HOURLY EQUIVALENT SOUND LEVEL (L_{eq})*
AS A FUNCTION OF TRAIN SPEED



EXAMPLE: Four car train averaging 65 mph on aerial structure travelling over a switch at 6-minute headways.

$L_{eq} = 63 + 5 + 5 - 1 = 72$ dB(A)

*Normalized to a distance of 50' from the centerline of the track.

ADDITIONS TO THE BASELINE L_{eq}

CONDITION	dB(A)
Tie & Ballast (Berm or Grade)	+0
Aerial Structure	+5
Switch on Berm or Grade	+3
Switch on Aerial	+5
Curve (Radius < 4500')	+5
2 Car Train	-3
4 Car Train	-1
6 Car Train	+0
8 Car Train	+1
10 Car Train	+2

COMPARISON OF BART AND COMMUNITY SOUND LEVELS

The hourly equivalent wayside sound levels (at a distance of 50 ft. from the centerline of the track) due to BART operations under present operating conditions are illustrated on Figure 21. Additionally, to facilitate a comparison, the range of the mean equivalent community sound levels has been indicated by the shaded band. It may be seen that the sound levels generated by BART range from well below the community sound levels to, at most, 12 dB above the mean community sound levels.[1]

The equivalent sound levels due to BART operations as shown on Figure 21 indicate that the highest BART L_{eq} s are found adjacent to switches and curves on aerial structures. It may be seen that the highest levels observed on the entire system are found adjacent to switches and curves on the Daly City and Fremont lines. The L_{eq} values on these lines are somewhat higher than observed on the other lines due to the greater frequency of operation on the Fremont and Daly City lines.

The equivalent sound levels attributable to the BART system tend to decrease as the observer moves away from the track. The equivalent sound levels in the community due to sources other than BART do not, in general, vary as a function of distance from the BART track. Assuming that the community sound levels remain constant, the relationship between BART and community sound levels at various distances from the track may be determined using Equation (4). When this is done, it is found that at a distance of 250 feet from the track, the BART-generated equivalent sound levels do not exceed the surrounding community equivalent sound levels by more than 4 dB at any location.

As a conservative means of assessing impact for this study, areas where acoustic impacts due to BART are considered at least possible will be defined as those areas where the BART L_{eq} exceeds the existing community L_d. In those areas where the BART L_{eq} exceeds the community L_d by more than 5 dB, acoustic impact due to the BART system will be considered probable.

The additive effect of BART sounds on the surrounding community sound levels is a rather minor element in a survey study such as the Phase I study program. As a worst case, if the BART L_{eq} and community L_d are equal, the total will be 3 dB higher than either of the two individually. Under any other conditions, the total sound level will be within 3 dB of the higher. As more information is developed concerning community response in the Phase II program, a formulation accounting for the additive effect may prove valuable.

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[1] Figures 22 through 25 indicate community and BART noise levels in more detail on a line-by-line basis.

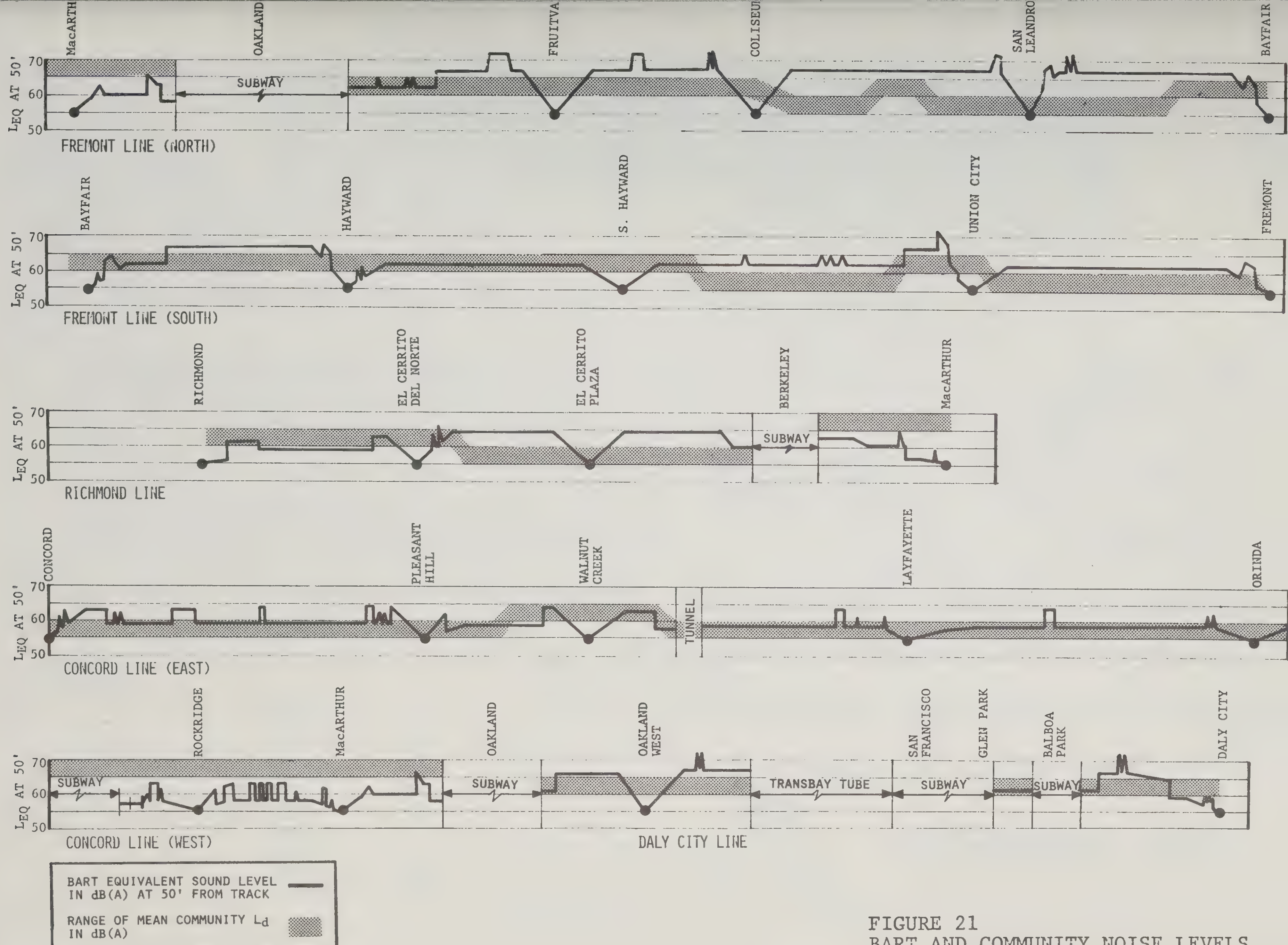
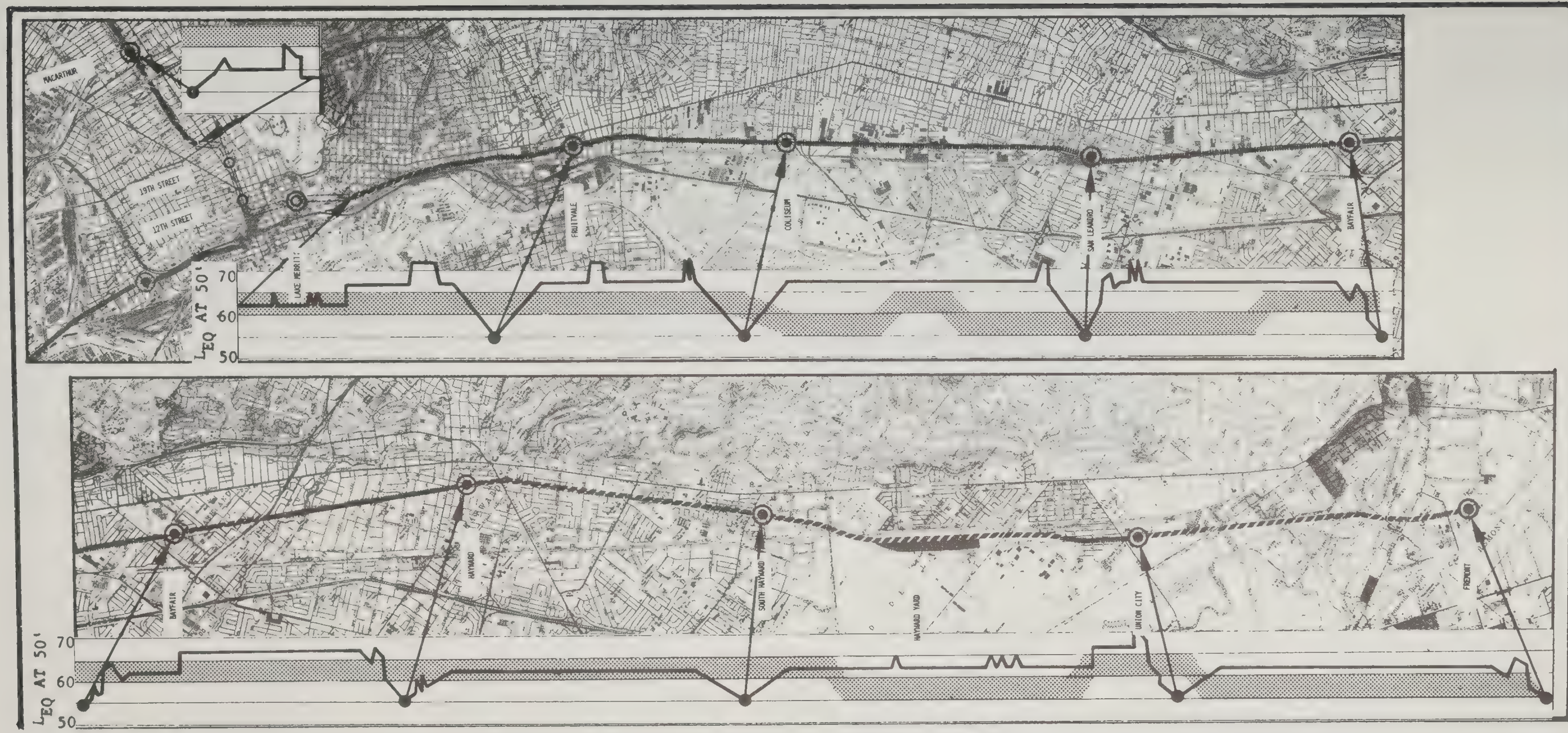


FIGURE 21
BART AND COMMUNITY NOISE LEVELS



LEGEND

BART EQUIVALENT SOUND LEVEL IN dB(A) AT 50' FROM TRACK

RANGE OF MEAN COMMUNITY L_d IN dB(A)

BART CONFIGURATION AND FACILITIES

SUBWAY LINE

SURFACE LINE

AERIAL LINE

ABOVE GRADE STATION WITH PARKING LOT

SUBWAY STATION WITHOUT PARKING LOT

SUBWAY STATION WITH PARKING LOT

MAINTENANCE/STORAGE

NORTH

THE ENVIRONMENT PROJECT

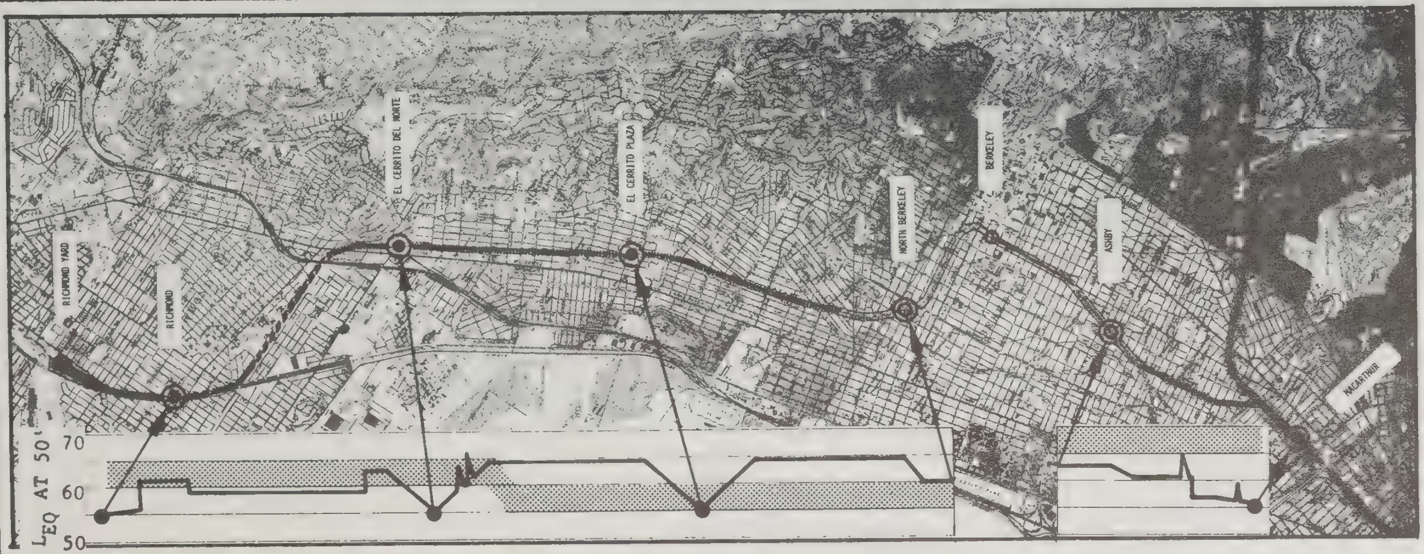
BART IMPACT PROGRAM

0 1 2 4 6 8

SCALE IN 1000'S OF FEET

FIGURE 22
COMPARISON OF BART AND COMMUNITY SOUND LEVELS

FREMONT LINE



LEGEND

BART EQUIVALENT SOUND LEVEL IN dB(A) AT 50' FROM TRACK	
RANGE OF MEAN COMMUNITY L_d IN dB(A)	

BART CONFIGURATION AND FACILITIES

- SUBWAY LINE
- SURFACE LINE
- AERIAL LINE
- ABOVE GRADE STATION WITH PARKING LOT
- SUBWAY STATION WITHOUT PARKING LOT
- SUBWAY STATION WITH PARKING LOT
- MAINTENANCE/STORAGE YARD

NORTH

THE ENVIRONMENT PROJECT

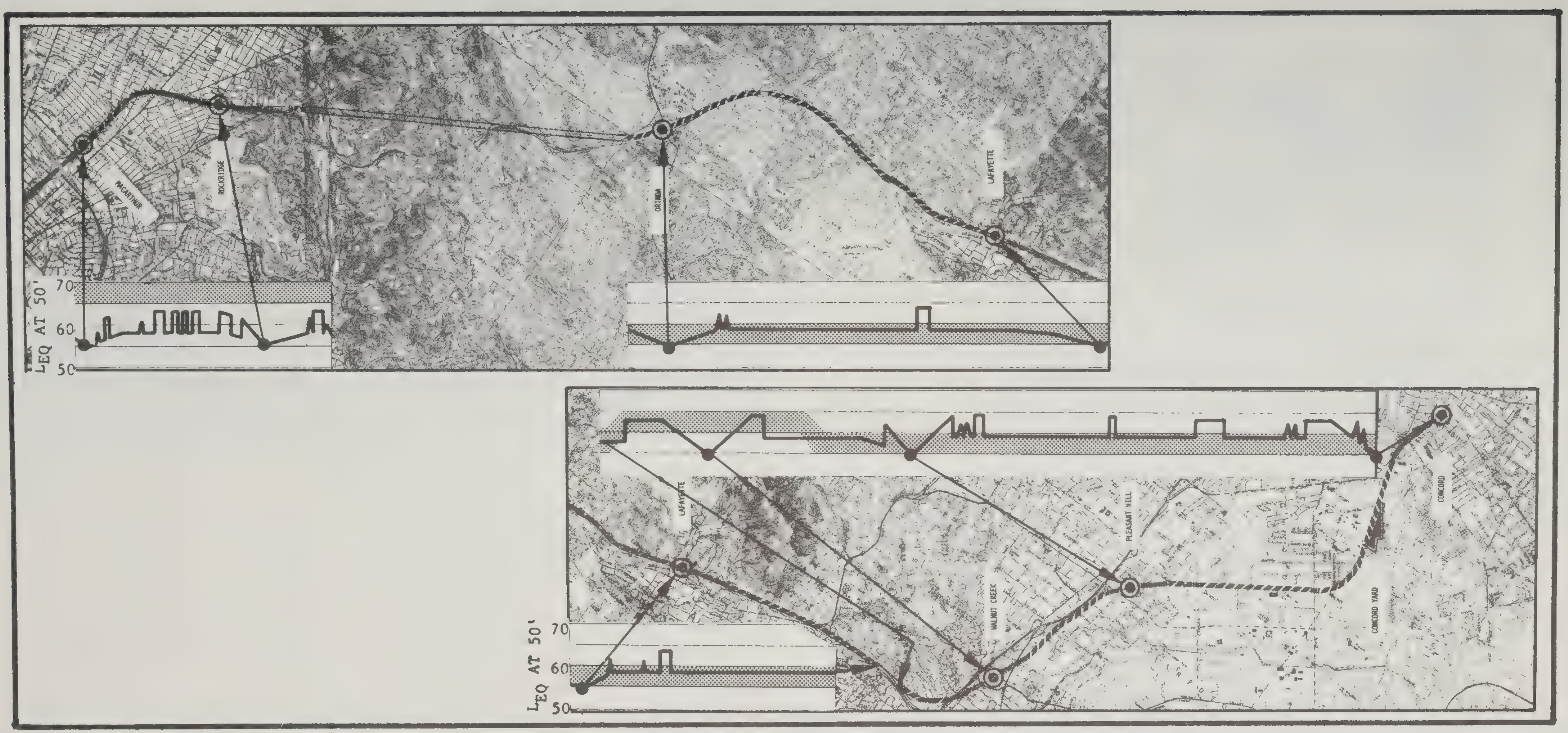
BART IMPACT PROGRAM

0 1 2 4 6 8

SCALE IN 1000'S OF FEET

FIGURE 23
COMPARISON OF BART AND COMMUNITY SOUND LEVELS

RICHMOND LINE



LEGEND

BART EQUIVALENT SOUND LEVEL IN dB(A) AT 50' FROM TRACK

RANGE OF MEAN COMMUNITY L_d IN dB(A)

BART CONFIGURATION AND FACILITIES

- SUBWAY LINE
- SURFACE LINE
- AERIAL LINE
- ABOVE GRADE STATION WITH PARKING LOT
- SUBWAY STATION WITHOUT PARKING LOT
- SUBWAY STATION WITH PARKING LOT
- MAINTENANCE/STORAGE YARD

NORTH

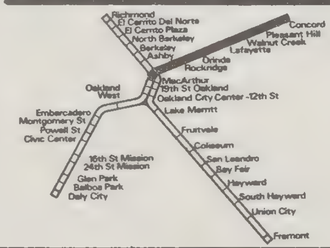
THE ENVIRONMENT PROJECT

BART IMPACT PROGRAM

0 1 2 4 6 8

SCALE IN 1000'S OF FEET

FIGURE 24
COMPARISON OF BART AND COMMUNITY SOUND LEVELS



CONCORD LINE

LEGEND

BART EQUIVALENT SOUND LEVEL IN dB(A) AT 50' FROM TRACK

RANGE OF MEAN COMMUNITY L_d IN dB(A)

BART CONFIGURATION AND FACILITIES

- SUBWAY LINE
- SURFACE LINE
- AERIAL LINE
- ABOVE GRADE STATION WITH PARKING LOT
- SUBWAY STATION WITHOUT PARKING LOT
- SUBWAY STATION WITH PARKING LOT
- MAINTENANCE/STORAGE YARD

NORTH

THE ENVIRONMENT PROJECT

BART IMPACT PROGRAM

0 1 2 4 6 8

SCALE IN 1000'S OF FEET

FIGURE 25
COMPARISON OF BART AND COMMUNITY SOUND LEVELS

DALY CITY LINE

Using the above assessment procedure, it may be shown using Figure 21 that along approximately 30% (21 miles) of the total BART system possible acoustic impact would be predicted, while along 10% (7 miles) of the system acoustic impact would be considered probable. If only the aboveground portions of the system are considered, that is if the underground or underwater portions are excluded, the percent of possibly impacted portions of the system rises to 40% while the probably impacted portion rises to 15%. These percentages are, of course, only of the total area within 250 feet of the center-line of the track.

The location of acoustically impacted areas along the BART system, as shown on Figure 21, has been combined with the census block population values to arrive at an estimate of the impacted population. These impacted populations are indicated by system line in Table 2.

TABLE 2
ACOUSTICALLY IMPACTED POPULATION ALONG THE BART SYSTEM

Line	Possibly Impacted Population	Probably Impacted Population	Total Impacted Population
Daly City	288	51	399
Richmond	0	2910*	2910
Concord	1182	0	1182
Fremont	8343	2319	10662
System	9813	5280	15093

*The BART L_{eq} along the Richmond line in general exceeds the community L_d by only 4 dB at a distance of 50 ft. from the track. However, due to the closeness (less than 50 ft.) of many of the residences to the system, probable rather than possible impact has been projected.

The equivalent sound levels illustrated on Figure 21 (both BART and community) are based on existing conditions. That is, BART during the course of this study operated only during the daytime hours and at scheduled train headways of either 6 or 12 minutes. Future plans for BART indicate that both train headway and hours of operation may be expected to change. An ultimate goal of 2-minute headways has been identified for part of the system. Such an increase in frequency of operation would be expected to result in an increased equivalent level of approximately 5 dB over the existing minimum headway of 6 minutes as is indicated on Figure 21. Thus, under such future daytime conditions, BART could be expected to generate sound levels in the community 10-15 dB higher than the mean community L_d. This would mean that rather than at a few isolated locations the BART-generated sound levels may be expected to exceed the mean community equivalent levels by 10 dB along much of the system.

An additional important factor concerning the relationship between sound levels generated by BART and those in the wayside community concerns nighttime operation. As has been previously mentioned, the sound levels at 12 locations along the system were monitored over a 24-hour period. The general trend of these data is that the late night and early morning sound levels tend to be on the order of 8-10 dB below the daytime levels. Thus, nighttime BART operations, while generating no more sound than present daytime operations, would be expected to be much more evident in the community. Even with 20-minute headways as have been projected for some of the late night operations, wayside sound levels at a distance of 50 feet from the centerline of the track of approximately 62 dB(A) would be expected adjacent to track on aerial structures. Assuming that the community sound levels would drop by 10 dB during the late night hours, such BART operations could well generate equivalent sound levels on the order of 15 dB or more above the community equivalent levels.

WAYSIDE VIBRATION LEVELS

As part of the overall study of BART acoustic phenomena, ground-borne vibrations were monitored at two points adjacent to the BART system. These measurements were designed to provide information concerning the character of BART-induced vibrations as well as the relative magnitude of vibrations caused by BART and other transportation sources. An extensive measurement program covering the broad range of variables such as ground type, distance from the BART line to the nearest structure, and basic dynamic characteristics of the structure on which the measurements were conducted was not within the scope of this program. As such, the measurements actually conducted represent a starting point from which the requirements for further study may be developed.

The actual measurements were conducted at two points adjacent to the BART system. The first point was on the foundation of a structure near the corner of 16th and Mission Streets in San Francisco. This location is nearly directly over the BART subway line running through San Francisco. The vertical vibration velocity of the ground was monitored over approximately a 4-hour period at this location.[1] During this period, more than 35 BART vehicle pass-bys in each direction occurred in the subway immediately below the measurement position. Analysis of the tape recorded data during this measurement program indicated that, with careful analysis techniques, at least the more prominent of the BART pass-bys could be identified and separated from other vibrations caused by vehicular traffic on Mission Street.

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[1] The vertical vibration velocity is the rate of movement of the ground, and may be expressed in either English (ft/sec) or metric (cm/sec) units. Alternatively, the vibration velocity level (VdB) in dB may be used where:

$$\text{VdB} = 20 \log_{10} \left(\frac{\text{Measured velocity}}{\text{Reference velocity}}\right)$$

The overall vibration velocity level in the 5-50 Hz region, which is commonly considered an indicator of human subjective response to vibration,[1] was not noticeably greater for BART pass-bys than for vehicular traffic on Mission Street. Indeed, the vibration velocity levels measured on the foundation of the subject structure seldom, if ever, exceeded what is commonly considered the threshold of perceptibility for vibrations.

The second measurement position was located in the City of Albany on a sidewalk near a BART aerial structure. The sidewalk represents a vibrating mass several orders of magnitude smaller than the structure on which the Mission Street measurements were conducted. Direct comparison of the levels measured at the two locations is complicated due to these differences in mass and to the differences in the surrounding soils. In qualitative terms, however, it should be expected that the vibration levels measured on the sidewalk should be considerably higher than those measured on the heavy structural foundation.

The actual levels measured on the sidewalk in Albany (approximately 30 feet from the centerline of the aerial structure) showed a marked increase during the pass-by of each BART vehicle. The overall vibration velocity level tended to rise on the order of 15-20 dB above the ambient as BART vehicles passed by. Additionally, the BART pass-by levels measured on the sidewalk were of the same order of magnitude as those caused by delivery trucks operating on the adjacent Masonic Avenue.

The overall vibration velocity levels measured at both locations were dominated by components in the 16 to 20 Hz range and components in the 25 to 35 Hz range. The components in the lower range correspond to wheel rotational frequencies on the trains. The source of the higher frequency component is less certain. However, a resonance of the track to the aerial structure isolation system might well account for the prominence of the vibration levels in the 25 to 35 Hz range.

The location of the Mission Street measurement position was such that it was not possible to obtain train speed information during each of the pass-bys. The Albany location, on the other hand, was very near a site used for one of the wayside acoustic measurement locations. During these acoustic measurements, the mean vehicle speed along this section of track as well as the normal variance of speed about the mean were determined. Applying this information to the monitored vibration velocity levels reveals a most interesting phenomenon. If the vibration velocity levels vary (as a first approximation) with the cube of the train speed (as does noise), the standard

[1] A recent study (Miwa and Yonekowa 1973) has shown that people's greatest sensitivity to vibrations lies in the 5-40 Hz region and that their reaction (subjective evaluation) is approximately proportional to the vibration velocity level. The threshold of perceptibility identified in this study is approximately 0.0035 in/sec. (rms).

deviation of the measured vibration levels would be expected to be approximately 3 dB. The standard deviation of the component corresponding to the wheel rotational frequency as measured, however, was less than 1 dB. Although by no means conclusive, this at least suggests that the wayside vibration velocity levels are less dependent on train speed than are wayside sound levels.

IV. CONCLUSIONS

The findings of this program may be examined individually and in conjunction with the findings of other studies to arrive at conclusions concerning the acoustic impact of the BART system on its environment. The conclusions in this section relate to a variety of interests concerning the BART system. They are intended as starting points for those who may have interests in differing aspects of the system. The first conclusion, taken in the narrowest sense, distills the entire acoustic impact study to a single conclusion dealing with the location of acoustically impacted regions. This conclusion may have significant implications for future system designs. The second and third conclusions are related primarily to the specific characteristics of the BART system, although they also have implications for the design of other systems. A fourth conclusion deals with the relative acoustic impact of the BART system to other modes of urban transportation. Finally, a conclusion concerning BART-induced community vibrations is presented.

- Impacted Regions

  Acoustic impact due to the BART system is focused on residences within 250 feet of the track centerline where there is unbroken line-of-sight from the residences to the track.

Acoustic impact, as the term is used in this report, occurs when the sound levels generated by the BART system project above the ambient community sound levels. The fluctuating characteristics of both BART and ambient community sound levels can be accounted for through the use of the equivalent sound level. Using L_{eq} levels determined from the program, BART sound levels in all cases are found to be less than 5 dB above the ambient at a distance of 250 feet from the track. Under most conditions, BART sound levels at a distance of 250 feet exceed the ambient even less due to the shielding effects of the first row of buildings along the track system. If commercial structures between the system and residential units are excluded, the first conclusion could be restated as: The acoustic impact of the BART system is most probable at the first row of houses within 250 feet of the system.

Specific procedures for the evaluation of the acoustic impact due to rail rapid transit systems have yet to be firmly established. The premise for the first conclusion--that impact is most probable where a new sound source increases the ambient by more than 5 dB--is drawn from procedures developed for the evaluation of highway traffic noise. The use of procedures developed for other types of transportation systems at best provides an initial estimate of the actual impact. The results of social surveys aimed at determining how people perceive BART-related sounds, combined with the physical sound

levels as determined in this study, will be necessary to provide a scientifically oriented means of acoustic impact assessment for rail mass transit systems.

- o <u>Major Determinants</u>

  Train speed, track type (tie-and-ballast and aerial), switches and sometimes curves are the primary factors affecting BART-generated sound levels.

The maximum A-weighted sound level at the wayside of the BART system has been shown to be proportional to 28 $\log_{10}$ of the train speed. This dependence on speed indicates that the wayside sound levels will vary approximately 8 dB from the lowest average speed on the system (36 mph) to the highest average speed sections of the system (70 mph). The mean wayside sound levels adjacent to tie-and-ballast track have been shown to be approximately 5 dB lower than those adjacent to trains on aerial structures for equal train speed. Combining the effect of speed and track type, it may be seen that the low speed tie-and-ballast is potentially 13 dB quieter than high speed aerial track. On either type of track, however, the presence of a switch or crossover results in a 5 dB increase in the wayside sound levels. Unlike the general sound level for tie-and-ballast or aerial track, however, the effect on the surrounding community due to a switch is quite localized. That is, the affected community takes on somewhat of a circular pattern surrounding the switch, rather than the long path or swath of affected communities surrounding the BART system in general.

- o <u>Prototype vs. Operational Sound Levels</u>

  The sound levels emitted by the BART system are nearly the same as were projected from measurement of prototype vehicles.

In a report prepared for BART in 1969 (Wilson, 1969), projections were made concerning the wayside sound levels that might be expected due to BART operations. The projections were based on a series of measurements of prototype BART vehicles operating on the initial test track. This report indicated that a wayside sound level at a distance of 50 feet from a train on aerial structure at 70 mph of 87 dB(A) might be expected. This projected level is indeed nearly the same as has been found for the mean sound level due to the operational 6-car trains on aerial structures. The 1969 report, however, indicated that the expected wayside sound levels adjacent to tie-and-ballast track would be only 2-3 dB quieter than adjacent to trains on aerial structures. This initial estimate has been found to be somewhat conservative in that a mean difference of 5 dB exists between aerial and tie-and-ballast track. Thus, while the initial estimate for trains on tie-and-ballast track has been found to be remarkably close to the actual levels

on the operational system, the projected value for trains on tie-and-ballast track was somewhat conservative.

- <u>BART vs. Other Transportation Sound Sources</u>

  Compared to two other modes of urban transportation (private auto or bus) conveying the same number of passengers per hour past a given point, BART generates marginally less noise in the community.

BART, operating with 10-car trains, could carry approximately 7000-seated passengers per hour in one direction (assuming 6-minute headways between trains). The hourly equivalent sound level at a distance of 50 feet from the centerline of the track under such operating conditions (at 70 mph) would be approximately 65 dB(A) for tie-and-ballast or 70 dB(A) for track on aerial structures.

At an average speed of 45 mph and with 1.5 passengers per vehicle, it would require approximately 4700-passenger cars to transport the same number of people. The wayside sound levels at a distance of 50 feet from the centerline of the highway carrying these vehicles would be approximately 73 dB(A). Similarly, at 45 passengers per vehicle at 45 mph, it would take approximately 156 buses to transport the same number of passengers. The hourly equivalent sound level at the wayside for this number of buses (assuming relatively quiet buses such as are in use by AC Transit or Golden Gate Transit) the wayside sound levels would be approximately 71 dB(A). Thus, buses would generate only slightly more noise than either trains on aerial structures or trains on tie-and-ballast track, while private passenger cars would generate slightly more sound than either bus or BART operations.

- <u>Community Vibration Levels</u>

  The ground-borne vibrations generated by BART appear to be of the same order of magnitude whether observed near either subway or aerial portions of the BART system.

The magnitude of the BART-induced vibration levels at both measurement locations was nearly the same as peak levels due to vehicular traffic on the adjacent streets. The magnitude of the vibration input of street vehicles at both locations should be very nearly the same. This indicates, at least qualitatively, that the level of BART-induced vibration is of the same order of magnitude at both locations.

V. IMPLICATIONS

Assessing the probable acoustic impact of a proposed urban mass transit system requires the evaluation of both the proposed systems and the likely alternatives to such a system. It is important to evaluate the scenario of events that is likely to take place if a certain system is not implemented as well as the conditions that will prevail if the system is implemented. The conclusions which have been reached concerning the BART system as well as certain of the findings which have not been specifically covered in the conclusions have implications regarding both the build and no-build alternatives of a proposed new system. This section presents implications which may be drawn from the findings and conclusions. As with the conclusions, these implications are presented only as an initial and partial array of those that may be drawn from the study. There is no doubt that others can and will be drawn.

- BART's Present Impact

  Serious acoustic impact appears unlikely along much of the 71-mile BART system at the present time. Maintaining the present relationship between BART and community noise levels as the frequency and hours of operation are increased will, however, require that additional noise control measures be taken.

- Major Determinants

  The area of probable impact due to the introduction of a new rail rapid transit system in an urban area may be evaluated based on projected wayside levels for the transit system and an evaluation of community wayside ambient levels. Track configuration, train speed, location of switches, and the frequency and hours of train operation would all influence the transit-system-generated wayside levels. Figure 17 provides an estimation of train-generated sound levels. The ambient sound levels in the community can be evaluated, at least on a first cut basis, using the population-density-based procedures developed for the Federal Environmental Protection Agency (Galloway et al, 1973).

- Special Determinants

  Switches and crossovers on the track system generate wayside levels approximately 5 dB higher than straight runs of track, regardless of specific track configuration. One means of reducing the impact of such switches on the community sound levels would be through installation of wayside barriers

designed to provide at least 5 dB of noise reduction. Through the use of such barriers, the level of impact adjacent to switches could be reduced to that of straight runs of comparable track.

- <u>Track Configuration</u>

  The roadbed configuration of a rail rapid transit system strongly influences the levels of sounds generated into the community. Based on acoustic impact alone, tie-and-ballast track on grade or berm is preferable to track on aerial concrete structures. The preference for track at grade is based not only on the higher wayside levels generated adjacent to track on aerial structures, but also due to the shielding (typically about 10 dB) that is usually provided by the first row of houses for trains operating at grade level. Shielding by the first row of houses is not usually the case for trains operating on aerial structures. Thus, for all but those residences located with direct line-of-sight to the track, wayside levels are reduced to nearly the level of the ambient or below.

- <u>Location</u>

  The siting of rail urban mass transit systems in the vicinity of existing major transportation arteries reduces the incremental impact of such a system. That is, sound levels due to rail mass transit systems tend to be about the same as those generated by other types of transportation such as automobiles or buses for the same level of passenger capacity. Thus, the sound levels generated by a new rail system would tend to be masked by the existing system.

- <u>Evening Operations</u>

  While the introduction of a rail mass transit system would appear to have a minimal impact during daytime and commuting hours, the operation of such a system during the late night and early morning hours has a much greater potential for impact. The general reduction of community sound levels on the order of 10 dB during the late night and early morning hours suggests that the number of operations on a given line would have to be reduced by a factor of 10 between the daytime and nighttime hours in order to result in an equal impact based on the relative difference between community and system generated sounds.

VI. ISSUES AND HYPOTHESES FOR CONTINUED STUDY

The current study has answered many of the questions concerning the acoustic impact of the BART system. Areas of potential impact along the system due to BART-generated sounds and some of the factors controlling BART-generated sounds have been identified. A means has been proposed for comparing the levels of sounds generated by BART to the community sound levels. These findings provide much of the information necessary for the assessment of the acoustic impact of the BART system. Not all of the questions concerning the system, however, have been answered.

The unanswered questions in this study have led to the identification of four aspects of the system where further study is advisable. The four identified aspects important to community impact are:

- The effect of maintenance procedures and vehicle aging.
- The effect of increased operational frequency and extended hours.
- The factors contributing to noise generated on curves.
- The relationship between BART configuration, location and community and BART vibration levels.

Each of these aspects and a brief review of the need for further study is presented below.

Aging and Maintenance

One of the aspects of the BART system planned to be studied during this program is the effect of aging and maintenance on wayside-generated sound levels. The system has not been in operation long enough to make such an assessment. In Phase I, a baseline or starting point has been established so that further measurements may be conducted during the Phase II program aimed at establishing the effect of maintenance and aging. Based upon an analysis of wayside sound levels measured during Phase II of the program, the effect of aging on the system and cars may be separated from the effects caused by maintenance practices and procedures. This information should be of use to the operators of the BART system as well as having significant implications for the design of future rapid transit systems.

Frequency and Hours of Operation

As has been mentioned in this study, increased frequency of operations (nighttime and weekend) is expected to significantly increase the acoustic impact of the BART system on the surrounding communities. A general estimate that the nighttime sound levels surrounding the BART system are some 10 dB(A) lower than the daytime sound levels has been made. Since little if

any quantitative data concerning community sound levels during weekend (as distinct from weekday) BART operations exists, it is important that the variation in community sound levels during evening, late night and weekend periods be closely examined during the Phase II program. This will allow the impact of BART during nighttime and weekend periods to be more clearly defined.

Curves

An area of significant importance for further study lies in the determination of the relationship between wayside-generated sound levels and track curvatures on the BART system. On a very qualitative basis, it has been determined that BART vehicles negotiating turns of radius less than 4500 feet tend to generate higher sound levels than the same vehicles operating on straight track. An exact relationship between train speed, curve radius, and other variables has not been determined. Based on the data obtained thus far, it has been hypothesized that the acceleration or deceleration of the BART vehicles through the curve may have a significant effect on wayside-generated sound levels. It is suggested, therefore, that the Phase II portion include a more comprehensive study of sound levels generated by BART vehicles as they negotiate curves.

Community Vibration Levels

This phase of the analysis program included a very limited series of vibration measurements in the community surrounding the BART system. It was intially hypothesized that vibration problems, should they occur at all, would occur in the vicinity of a subway or underground portions of the BART system. The findings of the initial study, however, are that ground-borne vibration levels are of the same order of magnitude whether adjacent to the subway portions of the BART system or adjacent to certain aerial structure portions of the system. Thus, significantly larger portions of the community surrounding the BART system may be subjected to BART-induced vibration impact than had been initially expected. A much more detailed analysis of the potential vibration-related impact of the BART system should be included in the Phase II study.

Since BART may generate vibration levels in the community which are perceptible and potentially bothersome, a comprehensive survey designed to assess the BART-induced vibration levels in the surrounding communities should be undertaken. This study should include determination of the factors which contribute to the generation of ground-borne vibration levels in the vicinity of the BART system as well as the characteristics of vibration transmission between the BART system itself and surrounding structures.

VII. METHODOLOGY

The study of the BART system-related sound levels as carried out for this program required that sufficient measurements be made to enable an accurate assessment of the system's acoustic impact, subject to budget and time constraints. Under such constraints, the establishment of precision and accuracy requirements compatible with the overall program goals was imperative. Specifically, the program had to be controlled in a way which ensured that the "forest" was not sacrificed for the "trees". That is, procedures required for an extensive study of individual system details had to be given a lower priority than procedures which led to a general characterization of the entire system.

The available information for the prediction of community response to noise, as summarized in the recent EPA "Levels" document (EPA, 1974), indicates that the relationship between sound level and response or impact is not precise. In other words, while a 5 dB change in sound level might indicate a probable change in response, a change in response attributable to a 1 dB change in sound level would not, in general, be predictable. This study seeks to distinguish between sound stimulus conditions which are likely to result in a difference in community response. Thus, the conditions under which BART train sound is measured and conclusions reported must be specific enough to yield stable (reliable) measurements relative to that 5 dB response-difference threshold. The values reported in this study for typical BART train sound at similar speed on tie-and-ballast (84 dB) and aerial track (89 dB) are within ± 0.3 dB of the true mean values, assuming normality and a 90 percent confidence interval. This is highly reliable. Further, 90 percent of the train pass-bys can be assumed to fall within ± 2.5 dB and ± 3 dB of these respective reported averages. This is far less variation than the apparent ability of most people to discern.

The precision of the measurement instrumentation used during the program has been controlled to ensure that the overall response of the data acquisition and reduction systems is within ± 1 dB in the frequency range of 20 to 10,000 Hz. The ± 1 dB measurement system precision requirement was arrived at following two basic lines of thought. First, using standard equipment and techniques in accordance with published specifications (ANSI SI.4-1971 and SAE J 184), a measurement precision of ± 1 dB is readily obtainable. Second, since the overall goal of the program was an accuracy of ± 2.5 dB, precision of less than ± 1 dB in the measurement and presentation of results could tend to be misleading.

INSTRUMENTATION

The instrumentation systems used for data acquisition during this study may be divided into three general types. The specific type of system used for a particular series of measurement was selected in accordance with both the

nature of the sounds being measured and the intended use of the data. This section will briefly discuss the specific components; procedures for use of the various systems will be outlined in the following section.

Figure 26 illustrates schematically the three types of field data acquisition systems used for this program. As may be seen, the first type of (direct reading) system consists of a random incidence microphone, microphone pre-amplifier and sound level meter. This system as used in the field conforms with the ANSI SI.4-1971 American National Standard for Sound Level Meters Type I. Before and after each measurement run, microphone sound level meter system calibration was made with an acoustic calibrator. Variations of more than 1/2 dB between the before and after calibration readings caused data during that particular test period to be disregarded.

The direct reading system was used primarily to supplement the wayside train pass-by data obtained using the continuous recording system described in the following section.

A continuous recording system consisted of the direct reading system with the addition of an instrumentation grade tape recorder. The microphone sound level meter tape recording system was calibrated before and after each measurement series with an acoustic calibrator. Additionally, the entire system was calibrated and adjusted in the laboratory so that an essentially flat frequency response between 20 Hz and 10,000 Hz was obtained. The continuous recording system was used for the on-board measurement program, the majority of the wayside measurement program, and a portion of the community measurement program. The procedures used will be described in the data acquisition procedure section.

The final tape system used during the measurement program has been termed the sampled recording system. Basically, this system consisted of the same equipment used for the continuous recording system with the addition of an electronic switching network which allowed the tape recording system to be cycled on and off over a definite time interval. The sampled recording system was set so that the record time was approximately 1.5 seconds for each sample and the dwell time between recorded samples was 28.5 seconds. The 1.5 on, 28.5 off sampling interval results in approximately a 20:1 reduction in recorded data over the sampling period. The 1.5 seconds "on" time was chosen to allow aural identification of the recorded events during playback while minimizing the effect of start up and stop transients in the recording system. The recording system used for this program has a dynamic range of approximately 55 dB(A). Previous measurements and analyses have indicated that this system produces results within 1 dB of the continuous recording for statistical levels between fifth and ninety-fifth percentiles.[1]

Figure 27 illustrates the data reduction systems used for this program. The general system consisted of the tape recorded data being played back through

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[1] See p. 63 for definition of percentiles.

FIGURE 26
DATA ACQUISITION SYSTEMS

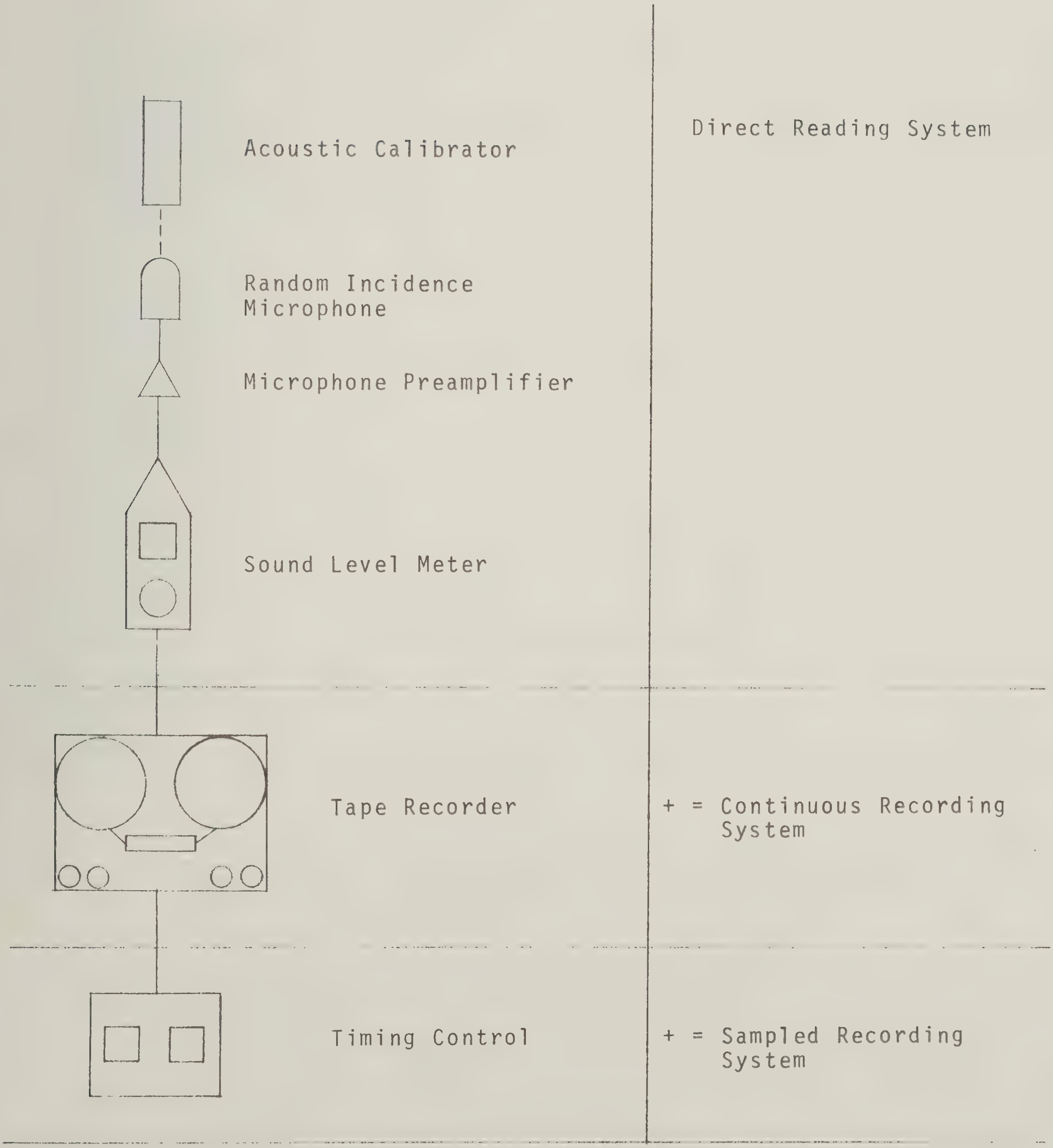
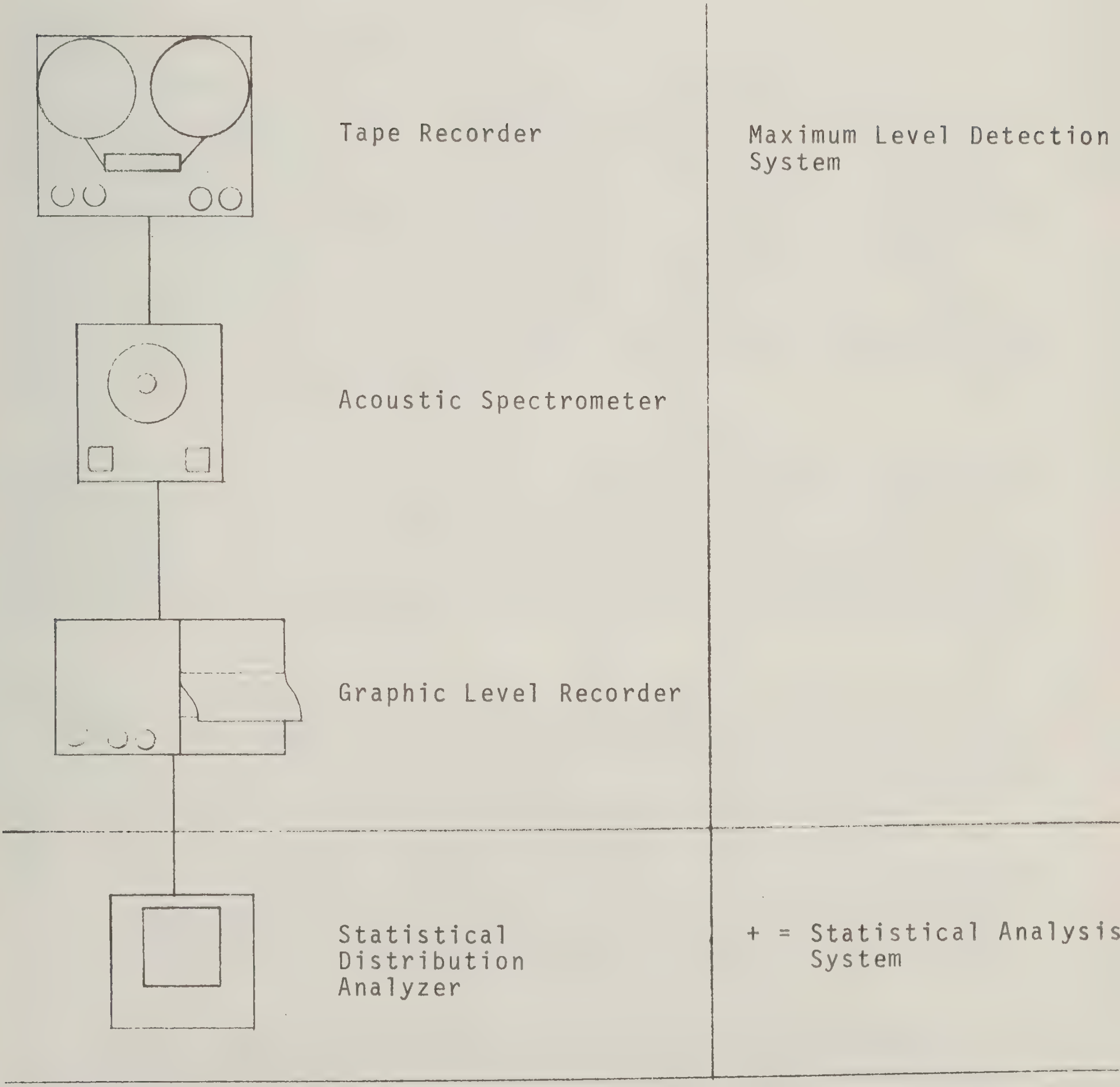


FIGURE 27
DATA REDUCTION SYSTEMS



a metering and filtering network (generally an acoustic spectrometer) controlling the input of a paper chart recorder which plotted the sound level in dB(A) versus time. In addition, statistical analyses of the sound levels monitored in the community were accomplished using an analog statistical distribution analyzer attached to the graphic level recorder.

DATA ACQUISITION PROCEDURES

All wayside measurements, whether using the direct reading system or the continuous recording system, were conducted with the microphone located at an elevation of 4.5 feet above the ground and at distances between 40 and 200 feet from the centerline of the nearest BART line. Previous studies conducted for the BART system (for example, Wilson, 1969) have shown that the variation in wayside sound levels as a function of elevation is of minor significance. Typically, the variation between the sound level at 4.5 feet and the sound level measured on the same elevation as an aerial track system have been less than 1 dB(A). On this basis, the additional efforts required to provide monitor locations at the same level as elevated structures were not considered justifiable for this program.

Using the continuous recording systems, the sound levels were recorded from the time a train could be visually observed approaching the test site until the time that the train could no longer be visually observed leaving the test site. Additionally, the time required for the train to pass the test position and the number of cars on the train were annotated on a second channel of the recording system. This information was used during the data reduction and analysis project to determine train speed.

During the recording process, the maximum A-weighted sound level observed on the sound level meter during the train pass-by was recorded on the annotation channel. After laboratory reduction of the sound levels, using procedures described in the next section, and comparison with the maximum levels observed in the field, it was determined that a difference on the order of less than 1 dB(A) between the field reading and the laboratory readings was typical. The data base generated during the initial series of wayside recorded measurements was expanded by an additional series of measurements using the direct reading system. In this case, the time that it took the train to pass the measurement position and the number of cars were manually recorded on a data sheet.

The continuous recording system was used for the on-board recording of sound levels throughout the BART system. For these measurements the microphone position was at a distance of 1.5 feet (0.5 meters) from the bottom center of the front outboard door in the lead car of the train on which measurements were being taken. This microphone location was chosen by subjectively searching for a spot where wheel noise was most easily heard. Thus, it is not appropriate to consider the sound levels obtained during the on-board measurement program as typical of the sound levels encountered by BART passengers.

The on-board sound levels were continuously monitored from one end point of the BART system to another. During this recording period, the car speed (obtained from the digital speed indicator located in the operator's cabin of the lead car) and position along the system (BART system mile post markers and visual siting of wayside measurement locations) were annotated by voice on the second channel of the on-board recording system.

The community measurements were conducted using both the continuous and the sampled recording system. The sampled recording systems were used to monitor the community sound level over a 24-hour period. The locations chosen for community monitoring were, in general, locations that were either far enough removed from the BART system or were acoustically shielded so that BART-generated sounds did not dominate the recordings.[1] In general, the measurement locations were approximately 250 feet from the centerline of the nearest BART track. The field of view of the actual BART system was typically less than 60°. The microphone locations for all community measurements was approximately 4.5 feet above the ground and a minimum of 6 feet from any hard reflective surface.

Measurements used to determine the variation in sound level from point-to-point in two neighborhoods (see Appendix A) involved the combination of the sampled and continuous recording systems. A central location was chosen in the neighborhood for monitoring of the sound levels with the sampled recording system. Simultaneously, 10-minute continuous samples were recorded at other locations throughout the neighborhood. Three continuous recording systems were used simultaneously with the sampled system. Ten coordinated 10-minute sampled periods were obtained using the three continuous recording systems located at strategic points throughout the community. The set of thirty 10-minute samples were subsequently statistically analyzed and normalized to the overall variation in community sound level (determined from the sampled recording system) during the entire measurement period.

DATA REDUCTION PROCEDURES

The on-board monitored sound levels were reduced using the acoustic spectrometer and graphic level recorded system. The plateau height of the sound level on various parts of the system was determined from the graphic level recording. The plateau height may be defined as the average maximum sound level observed during the pass-by. The type of track on which the train was running and the train speed for each of these plateau sound levels was deter-

[1] The "community" data were intended to document the sound levels in the absence of BART sounds. This separation was accomplished during the data acquisition rather than data reduction process as a means of minimizing the overall program costs.

mined from the data on the annotation channel. A regression of the sound level versus log of the train speed data was performed for the data obtained for trains on tie-and-ballast track and for trains on aerial structures separately. The 28 log speed relationship found during this portion of the program was used to normalize the effect of train speed on the data for the wayside measurement portion of the program.[1]

The wayside monitored sound levels were played back through the same spectrometer and graphic level recorder system described in the previous section. The maximum or plateau height of the sound levels monitored at the wayside were determined for each train pass-by and the train speed was calculated from the time of passing and the number of cars annotated on the second channel. The mean sound level and train speed were calculated for each of the measurement locations. In addition, the wayside sound levels were normalized to a constant speed using the 28 log speed relationship previously determined and the variations attributable to differences between individual cars or trains was determined.

All community data were reduced using the spectrometer graphic level recorder and statistical distribution analyzer system. The tapes were monitored during the playback process and all BART pass-bys in the recorded data were marked on the graphic level recording tape. Subsequently, the equivalent sound level for these BART pass-bys was computed and this computed L_{eq} was subtracted from the measured community sound levels. In this way, community sound levels unaffected by the BART system were obtained.

As a test for correlation between on-board measured sound levels and wayside measured sound levels, a series of measurements, both on-board BART trains and at the wayside, was conducted between the Pleasant Hill and Walnut Creek stations. During this series of tests, measurements were conducted on eight different BART cars. A total of 11 pass-bys at the wayside measurement position were made (two separate pass-bys were recorded on each of three of the cars).

As with other on-car measurements, car speed and position along the BART system were annotated on a second voice channel of the on-board recording system. In addition, the time at which the train was adjacent to the wayside measurement site was annotated. Using the annotated information during the data reduction process, the simultaneous sound levels on-board the train and at the wayside were determined for each pass-by. Using the pre-

[1] Normalizing the sound level produced by a BART train as it passes allows one to gain insight into the differences between different cars and between different segments of the system.

viously identified sound level versus distance relationship, all wayside sound levels were normalized to a distance of 50 feet from the centerline of the track and a 6-car train. Table 3 illustrates the on-board and wayside levels determined for these 11 runs. As may be seen, there is a consistent relationship between the on-board monitored sound level and the wayside monitored sound level. This relationship may be seen to remain constant for a given type of track even though the train speeds for the different runs and at different locations varied significantly.

VIBRATION MEASUREMENT PROCEDURES

The vibration measurements were conducted using the instrumentation illustrated on Figure 28. The accelerometer used has a flat (± 1 dB) frequency response from 1 Hz to more than 5000 Hz. The preamplifier was equipped with a 50 Hz low pass filter. Since human sensitivity to vibrations has been shown (Miawa, 1973) to be proportional to the vibration velocity over the frequency range of approximately 5-40 Hz, the 50 Hz low pass filter elimination of the unwanted high frequency signals allowed better use of the recording system dynamic range.

The tape recorder used to collect the vibration data has been specifically modified so that data may be recorded at 1/10 of the playback speed. This technique allows the recorder to faithfully record and reproduce signals from 2.5 to 2000 Hz. The recorded data were processed through an integrating amplifier system during the analysis process. Thus, the recorded acceleration data were converted to velocity for the analysis. A final shaping filter was used so that time-histories of the overall vibration velocity levels in the range of 5 to 50 Hz were plotted on the graphic level recorder.

TABLE 3

SUMMARY OF DATA FROM ON-BOARD/WAYSIDE
MEASUREMENTS BETWEEN PLEASANT HILL & WALNUT CREEK STATIONS

						(L_{max} - L_{PT})			
						Position 1 Aerial		Position 2 Tie & Ballast	
RUN #	DIRECTION*	L_{max_1}	L_{max_2}	L_{PT_1}	L_{PT_2}	NB	SB	NB	SB
1	NB	88	84	83	82	5		2	
2	SB	77	68	76	71		1		-3
3	NB	88	84	83	81	5		3	
4	SB	86	80	86	84		0		-4
5	NB	88	84	83	82	5		2	
6	SB	77	69	76	72		1		-3
7	NB	88	84	84	83	4		1	
8	SB	85	78	85	82		0		-4
9	NB	88	85	83	82	5		3	
10	SB	78	69	78	73		0		-4
11	NB	89	83	84	81	5		2	

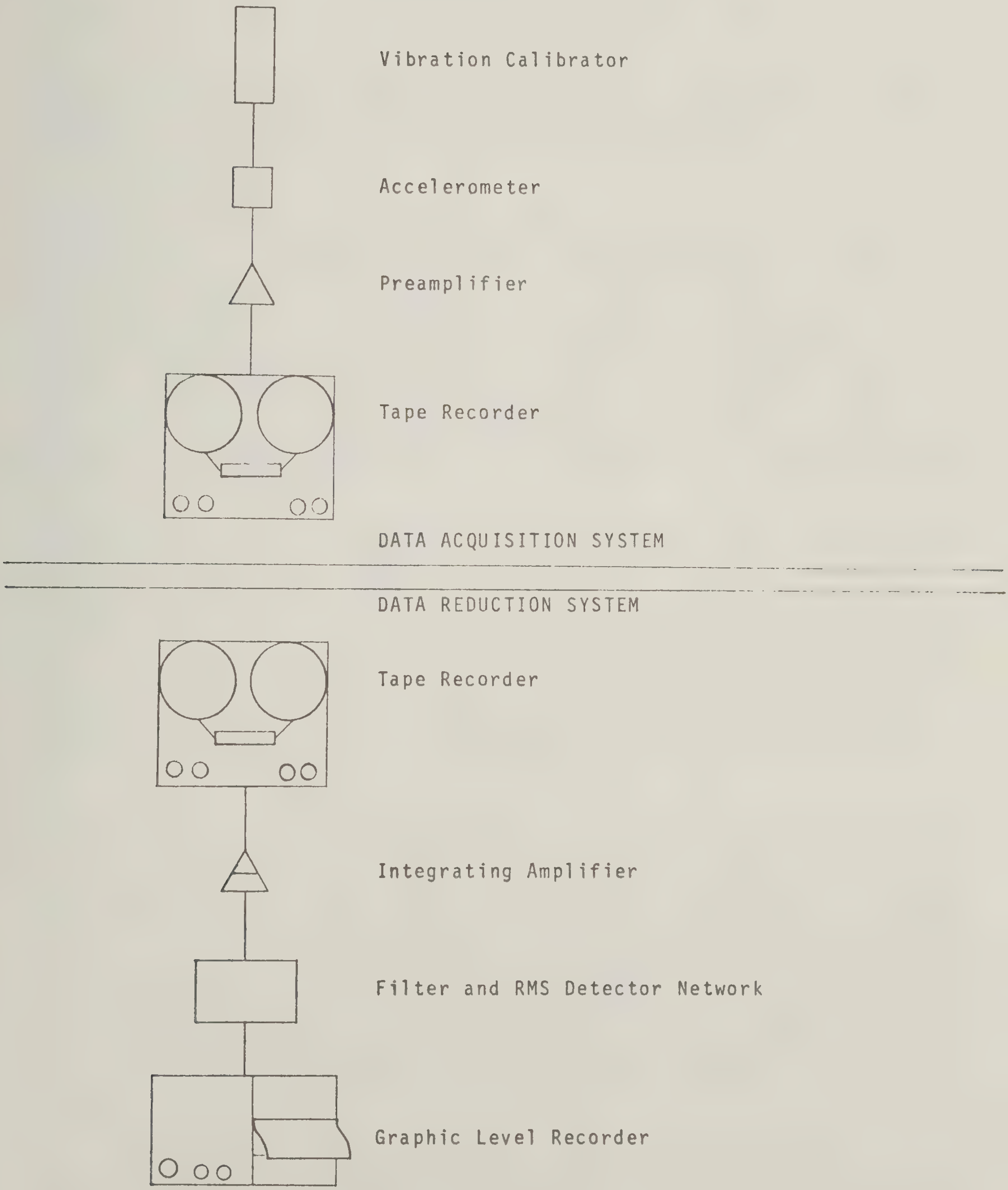
L_{max_1}, L_{max_2} = Peak train pass-by sound levels** at Positions 1 and 2. (Both positions are on NB side of system.)

L_{PT_1}, L_{PT_2} = In-car sound levels as train passed measurement positions.

* NB = North Bound Train
SB = South Bound Train

** Normalized to a distance of 50 feet from the track centerline for a 6 car train.

FIGURE 28
VIBRATION DATA INSTRUMENTATION SYSTEMS



APPENDIX A

Terms

Sound is a pressure fluctuation in the atmosphere. The magnitude of the sound describes the physical magnitude of this fluctuation in air pressure. Loudness, on the other hand, refers to people's subjective evaluation of the sound when they hear it.

Magnitude is stated in terms of the amplitude of the pressure fluctuation. The difference in magnitude between the faintest audible sound and the loudest sound the ear can withstand is so enormous (1,000,000,000:1) that it would be very awkward to express sound pressure fluctuations directly in pressure units. Instead, this range is compressed by expressing the sound pressure magnitude on a logarithmic scale. Thus, sound is described in terms of the sound pressure level (L_p) which is equal to ten times the common logarithm of the ratio of the squares of the sound pressure in question to the square of the stated or understood sound reference pressure (usually 20 micropascals).

The physical measure corresponding to the subjective aspect of pitch is the frequency of sound: the rapidity of the repetitive pressure fluctuations as expressed in the number of cycles completed per second. The recently adopted international standard of frequency corresponding to the old cycles per second (cps) is the Hertz, abbreviated Hz. The healthy young ear can hear sounds with a range of frequencies from about 20 to 20,000 Hz. As people get older, however, the acuity of hearing for higher frequencies gradually diminishes. So it is not uncommon for a 50-year-old man to be unable to hear sounds with frequencies above 8,000 Hz.

Most sounds are made up of a mixture of components having different frequencies: the sound of a diesel tractor-trailer at high speed on the freeway combines the high pitched singing sound of the tires and the low pitched roar of the engine exhaust, both of which the ear readily distinguishes. A landing jet aircraft has a clearly distinguishable whine from the compressor mixed with the random noise of the engine exhaust. A flute, on the other hand, if played softly, makes an almost pure tone containing a single prominent frequency. Depending upon how the components of a noise are distributed in frequency, our ears make a subjective judgement of the quality. Consequently, it is important to have an objective measure of the frequency distribution of a sound.

Such a frequency analysis is most often obtained by means of a set of filters tuned to different parts of the frequency range. These filters are electrical circuits, each of which eliminates (or filters out) all of the noise components

(except those in a more or less narrow band of frequencies) so that the meter reading of the sound level in only that one band can be made. Subsequent readings are made for all the other frequency bands. The end result is that the frequency distribution of the noise is described as partial sound levels in contiguous frequency bands covering the entire audible range. Usually, this set of numbers is plotted on a graph to show an octave band analysis of the noise. For some purposes, narrower bands-- such as 1/3 octave or 1/10 octave-- may be used. These plots of noise level versus frequency are referred to as sound level spectra. It may, in general, be stated that the finer the band-width used for analyzing environmental noise, the greater the time and expense for such an analysis.

One of the principal reasons for wanting a frequency analysis of a noise is that people not only distinguish the high frequency from the low frequency noise but also find high frequency noise to be much more annoying than low frequency noise at the same level. Therefore, to evaluate how disturbing each noise will be, it is important to know how much of the total sound energy is contained in each of the bands of frequency. This means keeping track of an entire set of frequency bands for each noise: usually, nine octave bands or twenty-five 1/3 octave bands in the frequency range from 31.5 to 8000 Hz! If the noise level fluctuates with time, the time varying level in each band must be accounted for. This accounting can pose a formidable task.

A-Weighted Sound Level

Fortunately, most of this complication can be avoided by the use of a special weighting network in the sound level meter. This weighting network is an electrical circuit which simulates the response of the average human ear to sounds of different frequencies. Each frequency of noise then contributes to the total reading in an amount approximately proportional to the subjective response associated with that frequency. Therefore, measurement of the overall noise with the sound level meter incorporating a weighting network yields a single number, called the A-weighted sound level, or A level expressed in decibels and abbreviated dB(A). The added letter "A", signifies that the sound level so expressed represents the weighted sound of all components of the noise. This single number rating has been found to correlate very well with people's subjective judgement of the annoyance of many types of noise, and is thus useful for evaluating various noise exposures in terms of the likelihood of public acceptability.

The A-weighted level has been chosen for reporting the findings of this study. The data obtained in the field, however, have retained (in analog form) the entire frequency content of the actual signal. It is possible, therefore, to reanalyze the data in terms of either octave bands or some additional, and as of yet undeveloped, weighting network which may better approximate subjective human response to environmental noise.

The dominant characteristic of urban noise is that it is not steady. At any particular location the noise will usually fluctuate considerably, from quiet in one instance to loud the next. Thus, the noise level at a site is not simply so many decibels. To describe the noise exposure adequately requires a statistical approach. Consequently, it is necessary to speak of the noise exposure of a site, meaning the whole time-varying pattern of the sound level, rather than the level at some single instant.

The problem which arises here is how to describe this time-varying pattern adequately. The usual description is statistical. Just as the U. S. Census Report describes the age distribution of the United States population by telling us that 90% of the population is over five years old, 50% is over 28 years old and 10% is over 60 years old, etc., so may we describe the noise exposure at a site by saying that the noise level at the site exceeds 51 dB(A) for 10% of the time, 45 dB(A) for 50% of the time and 39 dB(A) for 90% of the time. Such a description gives an idea of the average noise level as well as how much the noise level fluctuates. Since both the average level and the fluctuations are important to know (because a steady noise is more acceptable to most people than the noise of the same average value that fluctuates erratically), the use of the percentile statistical approach requires a minimum of three numbers at each point for an adequate description.

Complete description of the noise exposure would require a statistical breakdown of the sound level and percentage of time exceeded for each frequency band. For evaluating public acceptance of noise, however, it will suffice to express the noise in terms of the statistical distribution of the A-weighted sound level as described above.

Equivalent Sound Level - Leq

Fortunately from the standpoint of simplicity and clarity of presentation, there is an alternate methodology for specifying the temporal characteristics of noise which has been shown to substantially account for the average level and the time-varying characteristics of noise. This measure is the Equivalent Sound Level (L_{eq}). The Equivalent Sound Level is the equivalent steady noise level (A-weighted) that contains the same noise energy as would a time-varying noise during the same period.

The mathematical definition of L_{eq} for a time interval, defined as occupying the time between two instances, t_1 and t_2, is:

$$L_{eq} = 10 \log_{10} \left[\frac{1}{t_1 - t_2} \int_{t_2}^{t_1} \frac{P_t^2}{P_0^2} \, dt \right]$$

Where: P_t = the time-varying sound pressure

P_0 = a reference pressure taken as 20 micropascals

The L_{eq} can be thought of as the average (actually the logarithmic average since sound levels are in decibels) sound level over a period of time. Based largely on the good correlation between the L_{eq} value of community sounds and people's response to those sounds, the U.S. Environmental Protection Agency has adopted the L_{eq} as their standard unit for describing environmental sounds. A particular advantage of the L_{eq} concept in the study of the BART system is that the L_{eq} attributable to the fairly high level but short duration sounds of BART may be compared directly to the L_{eq} of the community without BART.

Various schemes using the L_{10}, L_{33}, L_{50} (the levels exceeded 10, 33 and 50 percent of the time respectively) or other statistical levels are currently in use. The rather small percentage (typically less than 5%) of time that BART generated sounds are audible in the community, however, makes the use of these other descriptors somewhat difficult. An analogous situation may be found in the vicinity of airports where the use of measures similar to L_{eq} has been common practice for many years. The use of measures similar to L_{eq} around airports has been used to account for the effect of rather short duration, though perhaps high level, sounds. Thus, there seems to be ample precedent for the use of the L_{eq} concept in the evaluation of the BART system.

Daytime Equivalent Sound Level - L_d

The equivalent sound level during the 15-hour daytime period (0700 to 1000 hours) L_d is the logarithmic average of the hourly L_{eq} values. The mathematical definition for L_d is:

$$L_d = 10 \log_{10} \left[\sum_{i=1}^{15} \frac{\text{Antilog}_{10} \left(\frac{L_{eqi}}{10}\right)}{15} \right]$$

Where: L_{eqi} = Hourly L_{eq} values for each of the 15 daytime hours.

Typical Neighborhood Acoustic Environments

The preceding section introduced the concept of the time-varying characteristic of sound levels in the urban environment. Another facet of urban sound is that significant variations in level from point-to-point, even within individual neighborhoods, are the rule rather than the exception. Residences near the major arterials in a neighborhood will commonly be subjected to sound levels 10-15 dB higher than their neighbors located on less traveled side streets or cul-de-sacs. The following examples of the sound levels in neighborhoods adjacent to the BART system will perhaps help to illustrate the variations in level that often occur from point-to-point.

Urban Neighborhood

Figure 29 illustrates the L_{eq} measured in El Cerrito adjacent to the BART system during a typical weekday, mid-morning and afternoon period. The L_{eq} levels indicated were determined through a series of simultaneous measurements over a period of approximately 6 hours. The numerical values shown are the averages over this 6-hour period.

Locations 1 through 3 are typical of many residential locations adjacent to a well traveled arterial, in this case Stockton Ave. Locations 4, 5, 7 and 8 on the other hand are less heavily traveled side streets (Liberty and Elm Streets). Locations 6 and 9 are adjacent to a street (Richmond Avenue) whose traffic flow rate is somewhere between the previous two. In numerical terms, Stockton Avenue carries approximately two and one half times as many vehicles per hour (420 vs 175) as does Richmond Avenue, while Elm and Liberty Streets carry proportionately less.

The general trend indicated on Figure 29 is an increase in the sound level accompanying an increase in traffic level. Such a trend is in accordance with published (Porter et al 1974) information concerning the relationship between traffic flow rates and curbside sound levels in the San Francisco Bay Area. In fact, using the traffic noise level nomograph illustrated in the above referenced document and traffic count information supplied by the City of El Cerrito, the measured and predicted sound levels agree within 1 dB(A).

Location #4 illustrates that even though traffic generated sounds dominate most locations in the urban environment, there are other important sources. Directly across the BART line from Location #4 is a school playground. During the measurement period, the acoustic environment at Location #4 was often dominated by the sounds of children at play in the schoolyard.

Suburban Neighborhood

The neighborhood illustrated on Figure 29 can be classified as a rather densely populated, single-family dwelling, urban neighborhood. Figure 30 illustrates the L_{eq} levels during a comparable daytime period in the Pleasant Hill area. It may be seen that the levels indicated on Figure 30 are generally lower than those indicated on Figure 29.

The only street on Figure 30 for which traffic flow rate information is available is Las Juntas, the busiest street in the neighborhood. With a flow rate of approximately 120 vehicles per hour, Las Juntas is quite comparable to Richmond Avenue as illustrated on Figure 29.

FIGURE 29
TYPICAL URBAN RESIDENTIAL
NEIGHBORHOOD - EL CERRITO

FIGURE 30
TYPICAL SUBURBAN RESIDENTIAL
NEIGHBORHOOD - PLEASANT HILL

Examination of Figures 29 and 30 will show that the L_{eq} levels (and most other measures of the sound as well) vary considerably from point-to-point in the same neighborhood-- even though the points may only be separated by a block or less. The range from highest to lowest in the El Cerrito neighborhood was 17 dB(A), while in Pleasant Hill a range of 13 dB(A) was found. Such ranges are typical of urban and suburban neighborhoods. In fact, should a neighborhood border on a major arterial (such as San Pablo Blvd. in El Cerrito or Treat Blvd. in the Pleasant Hill area), a range of 20-25 dB(A) or more would be expected.

The primary point to be made in this discussion of neighborhood acoustic environments is that no single number will suffice to completely characterize a whole neighborhood. With normal ranges of 10-20 dB(A) from block to block - depending on traffic flow and other conditions, any level selected can only be thought of as an average. Variations above and below the average must be expected based on quite localized conditions.

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ENVIRONMENT PROJECT PHASE I DOCUMENTATION

- Interpretive
  Summary*
- Environmental Impacts of BART*
  Interim Service Findings (1976)
- Acoustic Impacts of BART*
  Interim Service Findings (1976)
- Impacts of BART on Air Quality*
  Interim Service Findings (1976)
- Impacts of BART on the Natural Environment*
  Interim Service Findings (1976)
- Impacts of BART on the Social Environment*
  Interim Service Findings (1976)
- Impacts of BART on Visual Quality*
  Interim Service Findings (1976)
- Theory Background for Study of BART's Impacts
  (1976)
- Pre-BART Data Analysis
  (1975)
- Community Monitoring
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- BART and Its Environment: Descriptive Data
  (1976)
- Research Plan*
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